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ABSTRACT

This report describes the development of several new computer based strategies for teaching troubleshooting principles to electronics technicians. The computer programs to implement these strategies were developed in part from software produced in previous contracts. The report documents an experiment in which those materials were presented to student technicians to determine their attitudes toward the techniques, and to determine whether the training resulted in improvement of their technical skills. Results in both cases were positive with students responding very favorably to the materials and with their performance improving quantitatively and qualitatively after the instruction. The computer based techniques used are explained and examples of student interaction with the materials are included in the report. Copies of the tutorial materials used in conjunction with the on-line computer presentations are presented in an appendix. (Author)

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AFHRL-TR-76-68

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REACTIVE LEARNING ENVIRONMENT FOR COMPUTER ASSISTED ELECTRONICS INSTRUCTION

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This report describes the development of several new computer based strategies for teaching troubleshooting principles to electronics technicians. The computer programs to implement these strategies were developed in part from software produced in previous contracts. The report documents an experiment in which those materials were presented to student technicians to determine their attitudes toward the techniques, and to determine whether the resulting training resulted in improvement of their technical skills. Results in both cases were positive with students responding very favorably to the materials and with their performance improving quantitatively and qualitatively after the instruction. The computer based techniques used are explained and examples of student interaction with the materials are included in the report. Copies of the tutorial materials used in conjunction with the on-line computer presentations are presented in an appendix.

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SUMMARY

PROBLEM

The training of troubleshooting principles has always been difficult in the military and civilian community. Techniques which have proven to be successful have also been expensive and labor intensive. Within electronics training, this has proven to be especially true, probably due to large variety of devices and technologies which are used in military equipment. This continuing investigation has attempted to develop methods for applying computer-based simulation techniques to assist in the training of electronic technicians more thoroughly and less labor intensively than must be done currently. The goal has been to develop in the student an understanding of the cause and effect relationships between circuit elements, by enabling the computer to interact with the student in English as he is led through an investigation of the operation and repair of a malfunctioning electronic device. The development of programming and pedagogical techniques to achieve this end has been the focus of this research.

APPROACH

This report documents the development of an existing system into a 12-hour sequence of instruction on the principles of electronic troubleshooting. One aspect of this system is documented in TR-76-67 which was an interim technical report required under this contract. The work done in the second phase of this contract was the development of a computer assisted instructional situation in which an expert tutor (simulated by the computer) could be observed and conversed with as it performed debugging of a fault inserted by the student. This additional technique was then integrated with existing laboratory simulation techniques developed under prior contracts to provide a complete instructional block. An experiment was run to determine the utility of these training techniques when used with students in a technical training institute. Students were presented the sequence of materials and were evaluated at various points within the sequence and questioned to determine their attitude toward this type of instructional presentation.

RESULTS

Student attitudes toward the computer simulated laboratories, expert tutors, and gaming situations were overwhelmingly favorable. All felt that they significantly improved their diagnostic skills, particularly because of their ability to interact repeatedly with the simulated laboratory equipment and their observations of the 'expert troubleshooter' simulated by the computer. They additionally felt relaxed and unthreatened by the computer and felt that it was generally easy to deal with. Testing administered to the students show positive improvements in both time required to diagnose, and in the techniques used to isolate faults after training.

CONCLUSIONS

The intense, intelligent training environment created by using the computer's unique ability to simulate and generate appropriate instructional sequences could result in positive improvements in student understanding of troubleshooting techniques and attitudes toward training of these and probably related problem solving skills. The use of the computer to eliminate technical problems with handling laboratory equipment in this type of instruction enhances the student's ability to develop the underlying skills required for troubleshooting by enabling him to concentrate on these skills.

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Reactive Learning Environment for Computer Assisted Electronics Instruction

Chapter 1

INTRODUCTION

SOPHIE (i.e. SOPHisticated Instructional Environment) is an intelligent, generative instructional system for teaching the knowledge and reasoning strategies of expert-grade electronic troubleshooting. This report describes a study which explores the strengths and weaknesses of an extended SOPHIE system. This study has helped to develop a better understanding of how SOPHIE's unique capabilities can be exploited in a training environment.

At the same time we wanted to investigate how simpler systems designed in the spirit of SOPHIE but less ravenous of computational resources could augment some of SOPHIE's tutorial capabilities. In particular, the original SOPHIE was not a self-contained tutorial system. To obtain maximal utilization of its capabilities, a more complete computer-based learning environment had to be built around it which combined the best features of traditional frame-oriented lessons, laboratory simulation exercises, and other simpler but still generative instructional material. In this report we describe this computer-based learning environment, along with the series of formative experiments we conducted in order to successively refine this environment.

Specifically, we hoped the experiments would shed some light on several issues: How can sophisticated artificial intelligence systems augment frame-oriented Computer Assisted Instruction (CAI)? How can students be helped to exploit a learning environment which is open, non-directed, and rich. What elements in a computer-based course contribute most to student enjoyment, involvement, and productive learning? While these are certainly very broad questions which we do not hope to answer completely, our experiments provide an example of a learning environment which provides positive results in these terms.

Brief Description of SOPHIE

In order to understand the reasons for extending SOPHIE and for performing the experiments described here, a brief description of the kernel SOPHIE system is in order.

The original, kernel system is now called the SOPHIE lab to distinguish it from the rest of the extended SOPHIE system. The SOPHIE lab consists of a large collection of artificial intelligence programs which use a circuit simulator to answer hypothetical questions, evaluate student hypotheses, provide immediate answers to a variety of measurement questions, and allow the student to modify a circuit and discover the ramifications of his modifications. To enable students to carry on a relatively unrestrained English dialogue with the system, the SOPHIE lab has a flexible and robust natural language front-end.

In a typical instructional session, based solely on the SOPHIE lab, a student is presented with a fault of some specified degree of difficulty. He then tries to debug the instrument by requesting measurements. At any time he can offer a hypothesis about what he thinks could be wrong with the instrument and receive an evaluation of his hypothesis in terms of the measurements he has made. The student can also, at any time, request that a component be replaced. Before the part is actually replaced, the student is required to say exactly what he thinks is wrong with it. Only if he is correct is a new component put in the circuit. If he is incorrect, the hypothesis evaluator is invoked automatically to determine whether his proposed fault is reasonable, and if not, why not. Because some faults in the instrument blow out other components, finding a faulty component will not necessarily fix the instrument. Indeed, in such cases where the replaced part is actually a "secondary fault," the replaced component will be blown again. As in the repair of real instruments, the fundamental underlying fault must be diagnosed and repaired first.

From the above description, it can be seen that a student using just the SOPHIE lab needs an understanding of the particular circuit being simulated, some reasonable troubleshooting strategies, a basic knowledge of electronics, and the ability to generate plausible hypotheses.

The Learning Environment

One of the primary goals of these experiments was to determine if trainees could really take advantage of the freedom provided by this environment. Previously, we had verified that many of SOPHIE's educational features could be exploited by engineering students, but we were less sure that these same features would be liked and used to good advantage by less academically oriented students studying to become technicians. In other words, we wanted to know if many of SOPHIE's capabilities were too sophisticated for many of its potential users. Consequently, the experiments undertaken in this study focussed on how technical students used, reacted to and profited from the total learning environment built on and around SOPHIE. The learning environment we constructed addressed all of these issues and, in fact, provided us with a rich opportunity to experiment with how to sequence various activities in order to optimize what students mastered.

Many electronic troubleshooters are trained to repair only specific pieces of equipment. These people have great difficulty fixing familiar devices with unusual faults or unfamiliar equipment for which they have no specific training. This is not the kind of troubleshooter we wish to develop. Instead, we are focussing on producing a skilled troubleshooter who is capable of fixing even unfamiliar pieces of equipment. Such an expert troubleshooter is often called on to fix the equipment with which others have failed, and is surely expected to be able to fix any of his own calibration or test gear. He is supposed to be able to handle new equipment without significant retraining. He must have a sufficiently good conceptual understanding of electronics to be able to develop appropriate diagnostic steps on his own, to digest new information from technical manuals.

One word of caution may be in order. Our goals were not to try to establish that SOPHIE-like environments obsolete more traditional frame-oriented instruction. Indeed, we tried very hard to design the best possible text and frame-oriented materials. Against that background we wanted to see how more sophisticated systems could further enhance a student's learning and motivation.

The learning environment consists of two new instructional subsystems built on top of the SOPHIE lab and a set of activities which structure the way students used both the lab and the new subsystems (see Figure 1). The first of these new instructional systems (described in more detail in Chapter 4) is called the Expert Debugger. This system can best be described as an articulate expert which can not only locate faults in the given instrument, but much more important, can articulate exactly the deductions that lead to it. That is, it can explain its particular top-level troubleshooting strategy, why it is making any particular measurement, what follows from the results of that measurement and what someone might mistakingly or prematurely conclude from that measurement. In brief, it instructs by first letting the student choose a fault (symptom) and then engaging him in a dialog as it progresses insightfully toward finding the fault. Instead of explaining abstract, uninstantiated troubleshooting

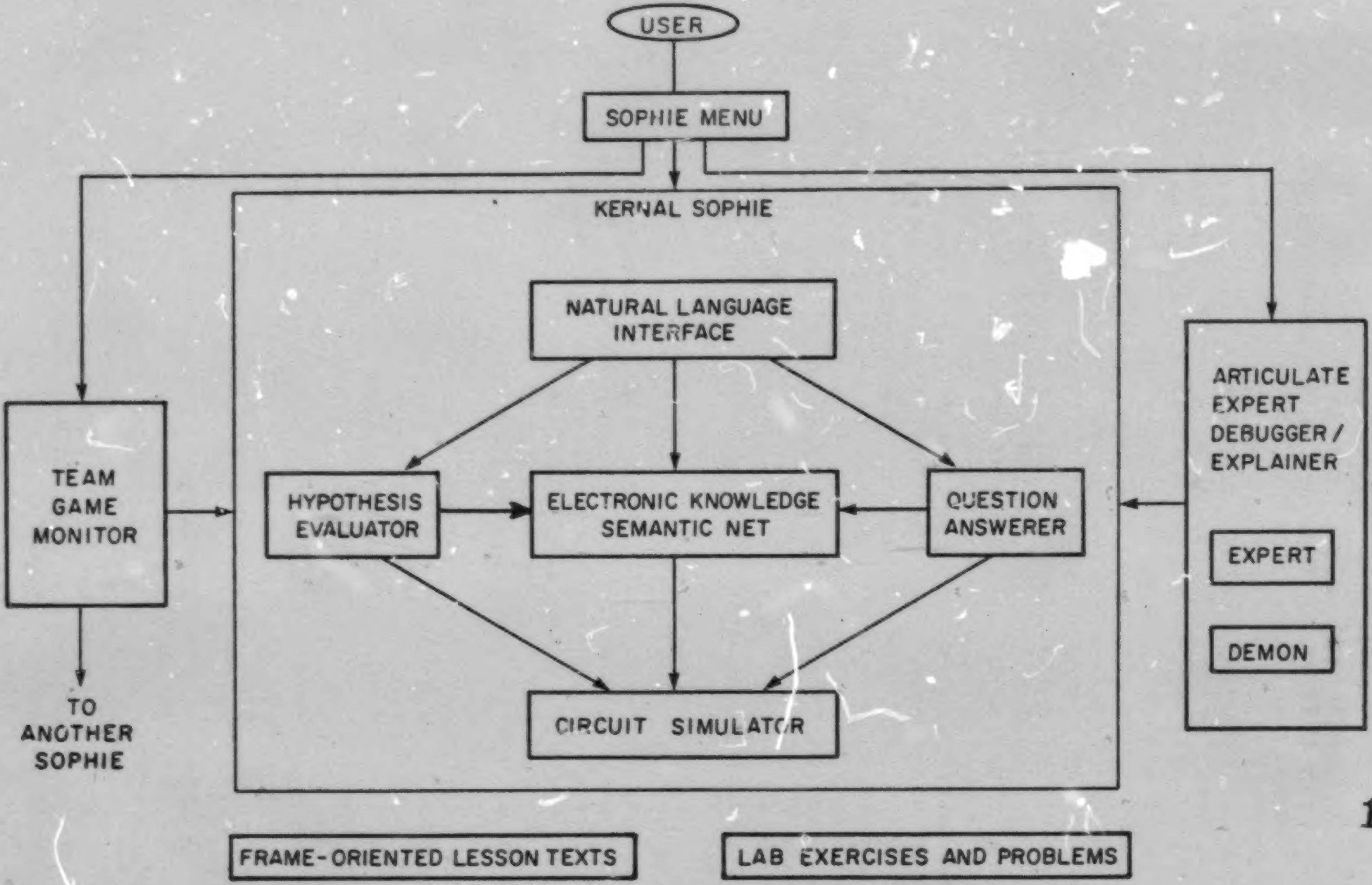
USER
SOPHIE MENU
KERNAL SOPHIE
NATURAL LANGUAGE INTERFACE
TEAM GAME MONITOR
HYPOTHESIS EVALUATOR
ELECTRONIC KNOWLEDGE SEMANTIC NET
QUESTION ANSWERER
ARTICULATE EXPERT DEBUGGER / EXPLAINER
EXPERT
DEMON
CIRCUIT SIMULATOR
TO ANOTHER SOPHIE
FRAME-ORIENTED LESSON TEXTS
LAB EXERCISES AND PROBLEMS

FIGURE 1

EXPANDED SOPHIE SYSTEM

strategies, we can, with this system, explain these expert strategies and the other pertinent electronics knowledge in terms of concrete examples* which stem from what the student has done!

The second instructional subsystem is a troubleshooting game (described in Chapter 3) which permits one team to insert an arbitrary fault and the other team to locate this fault by making measurements. The team that inserts the fault must not only be able to predict all of its consequences (such as other parts blowing out), but must also be able to qualitatively predict the outcomes of any measurement the opposing team requests. In brief, students playing this game exercise their troubleshooting techniques, while developing their understanding of how the circuit functions.

Typical Sequence of Activities

The experiments we conducted were carried out in the context of a short "course" on electronic troubleshooting. The sequence of activities in the course was constructed to take approximately 12 hours. The first two hours (of the twelve) consisted of a brief introduction to the SOPHIE laboratory followed by an intensive study of the instructional booklet (see Chapter 2). The booklet provides review material on basic electronics as it pertains to regulated power supplies and a more detailed explanation of the particular power supply to be used. This material was followed up by a question answering period and an informal discussion on troubleshooting strategies.

In the second three-hour period, students alternated between using the Expert Debugger and doing troubleshooting in the SOPHIE lab using preselected faults. Unassisted troubleshooting provided good impetus for paying close attention to what the Expert was saying; the students quickly realized that troubleshooting this instrument was quite a bit more complicated than they first suspected.

The third session consisted of two activities. The first exploited SOPHIE's simulator fully -- students were given the task of finding faults which would propagate to cause a specified component to blow out. The purpose of this activity was to give them practice in predicting possible causes of secondary faults. This kind of understanding is otherwise hard to come by and, needless to say, failing to acquire it can lead to very inefficient, expensive troubleshooting.

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*This subsystem, not an overly complex program (as compared with the SOPHIE lab), gets most of its power by having its knowledge encoded in terms of augmented decision trees. As such, it is an interesting example of smaller generative systems.

After these exercises were completed, the students formed two-person teams and engaged in more troubleshooting practice. As we discuss below, the use of teams at this point proved to be very beneficial, generating a great deal of discussion about what measurements to make and why.

The last three-hour period saw teams pitted against each other in the troubleshooting game. At this point we turned on the costing function which assigns realistic costs to measurements they were making. After several go-rounds with this activity, we broke up the the groups and gave each individual some final troubleshooting exercises. For this final activity we stressed cost-effective troubleshooting as well as the use of the hypothesis evaluator in SOPHIE.

The Experiment

In order to explore how best to exploit the novel instructional capabilities made possible by SOPHIE, and how students reacted to and learned from this environment, we designed a set of formative, exploratory experiments.

To ensure that the results of these experiments would be relevant to the electronics training program in the Air Force, we needed to find a population which had educational backgrounds and capabilities similar to personnel chosen for expert level training in electronics. Toward this end, we visited numerous technical and vocational schools and finally settled on students part of the way through the second year of a two year electronics technician program at Wentworth Institute of Technology in Boston, Massachusetts. These students are likely to be comparable to trainees two-thirds through an extensive one year program. These students had been taught basic transistor theory and had had a fair amount of laboratory experience. Their courses were not overly theory oriented but most of the students appeared to have a good qualitative understanding of basic electronics. They also appeared willing to participate in our experiments (undoubtedly due in part to the fact that they would be paid).

From the subjects responding to our request we randomly selected seventeen who were split into four groups. Two of these groups attended twelve hours of training distributed over four Saturday sessions. One group spent three hours on each of four successive days. A final group spent eight hours in a single day. This latter group was studied to see what would happen if we tried to concentrate all these activities into a short period.

Although the various training activities (and the sequencing of them) had minor modifications and refinements between experimental groups, the basic sequence of events followed the pattern described above. In addition to the scheduled activities we gave several tests in order to check their progress and to probe their weaknesses. We also conducted frequent informal interviews and, at the end of the training period, we gave an extensive questionnaire and conducted an hour-long group interview. These interviews were recorded and transcribed and are, in part, reproduced in Chapter 5 of this report. We also collected all of their troubleshooting protocols so we could analyze their difficulties and progress.

With the fourth (one-day) group we conducted a more formal study of what they learned. We gave this group a pretest in basic understanding of power supply troubleshooting and then two faults to actually troubleshoot. These tests were administered after they had finished the instruction booklet and had received an informal recitation on troubleshooting. Then, after they had finished all of the "laboratory" activities they were given a post-test which included some additional troubleshooting. The purpose of these tests was to examine the learning differential for this least favorable format -- short and highly concentrated. Further, we measured only the effect of the computer-based activities, rather than the combined effect of lessons plus computer activities. Thus, the effects we observed were over and above those obtained by good printed materials.

The remaining chapters of this report discuss in detail the material and programs designed and implemented for this study. The last chapter discusses at length the results of and examples from these formative experiments, hopefully conveying to the reader many of the insights that we gained in conducting them. Before we get into these details, we would like to present a more general view of the issues involved in the applicability of the SOPHIE system.

Learning Electronics While Troubleshooting

Although the original purpose of SOPHIE's computer-based learning environment was to teach troubleshooting skills, it has a much wider applicability than first realized. The troubleshooting scenario that SOPHIE supports also serves as an excellent pedagogical tool for crystallizing a student's knowledge of electronic theory.* Theory alone does not constitute a useful knowledge of electronics; it must be combined with intuition and practical experience. Indeed, it is the purpose of theory to unify and organize the vast experience of many people in a form which is easier to communicate and make predictions from. But what of the student who has little experience prior to learning electronics theory? He will learn many facts and relationships which will be, at best, an abstract body of knowledge for him. When such a student begins working in field situations, he has a great deal of conceptual relating and reorganizing to do.

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*Of course, a deep understanding of electronics is also essential to expert-level troubleshooting.

The SOPHIE environment has much to offer students who lack electronic intuition. The troubleshooting interaction establishes practical situations in terms of which relevant electronic theory can be explained. Thus, realistic problems are used to instantiate bits of theory, bringing the theory into a practical light. Having actual situations to replace the variables in theoretical relationships closes the loop, as it were, providing the facts which originally motivated the theory, so that a unified understanding results. Observations can be understood in terms of theoretical relationships and vice versa.

Some concrete examples of this interplay of theory and practical experience are in order. Ohm's law is a very basic relationship in electronics, stating that the voltage across a resistance is simply the product of the current through the resistance and the value of the resistance:

$$E = IR$$

where:

E is the voltage
I is the current, and
R is the resistance.

Students learn ohm's law on day one. They are told that it must always apply in DC circuits. They work out numerous problems which rely on the law. They know it well, in a theoretical sense. Nonetheless, students working with the IP-28 power supply are frequently observed to make the following error: They suspect that the current may be too high through the load resistor, even though they know the voltage across it is okay (given that the load resistance is okay). When this error is brought to the student's attention, the meaning and relevance of ohm's law becomes immediately clearer.

This is not an isolated instance. Another example concerns zener diodes. Our students had studied zeners, and "knew" that a working zener will react to keep the voltage across itself constant. Nonetheless, on seeing 40 volts across a 36 volt zener, many students miss the fact that the zener must be faulted. They may even be aware that the voltage is definitely wrong without suspecting the zener. Again a similar dialogue between the laboratory instructor and the student at this point is apt to lead to a more meaningful understanding of zeners.

The point is simply that theory, to be fully understood, requires practical examples within the student's experience to make it meaningful and useful. One of our goals is to have the SOPHIE environment provide just this sort of experience, in a readily absorbable form. The linkage of theory with experience is the stuff of which intuition is made. Even if troubleshooting per se were not a primary goal for electronics students, such experience proves to be invaluable because of the depth it imparts to their theoretical knowledge.

Chapter 2

LESSONS

This chapter describes our introductory booklet* which each student reads before starting to use the computer-based learning environment. The booklet is included in its entirety in Appendix II of this report. The intent of the booklet is to establish a common base of electronic knowledge, to provide general information about regulated power supplies and to present a good introduction to the IP-28 regulated power supply.

We used an interesting pedagogical technique to create this material. We sought an exceptionally clear way to explain the functional modules of the IP-28 and their interactions. The technique we used, in part, is to present a series of power supply designs, the first a drastically simplified hypothetical supply. We explain not only how this simplified version works, but more importantly, what its shortcomings are: why it is not an adequate power supply. We then propose a refinement to its design, creating a slightly more complicated hypothetical power supply. We repeat this process resulting in an evolutionary sequence of hypothetical circuits which finally converges on the real IP-28. For each successive version we discuss an identified shortcoming and how to compensate for it by adding a new component or module.**

We believe that such evolutionary sequences lead to a better intuitive understanding of the role of each component in the real instrument than does the usual sort of functional description often found in instruction booklets and technical manuals. Since each functional block undergoes its own evolution from primitive to realistic, not only does its intent in the actual circuit become more easily understood, but also how its purpose is realized. That is, both its extrinsic and intrinsic descriptions become understandable.

As an illustrative example of such an evolutionary sequence, as it is used in our introductory booklet, we present here the development of the Constant Current Source module, the functional block in the IP-28 which is perhaps the hardest to understand. The pedagogical challenge here is to find a way to explain this complicated and unobvious module so that the student will have an intuitive understanding of how it works. The complete circuit of the Constant Current Source is shown below:

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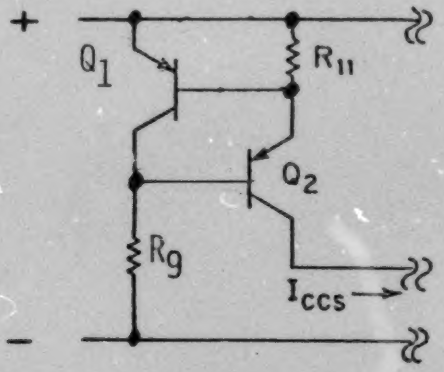
*This booklet also exists as programmed instructional material wherein after each "frame," questions are presented followed by the correct answers and/or remediation.

**These lessons are our first attempt to implement such a tutorial scheme and reflect it only to a limited extent.



Constant Current Source

Figure 1

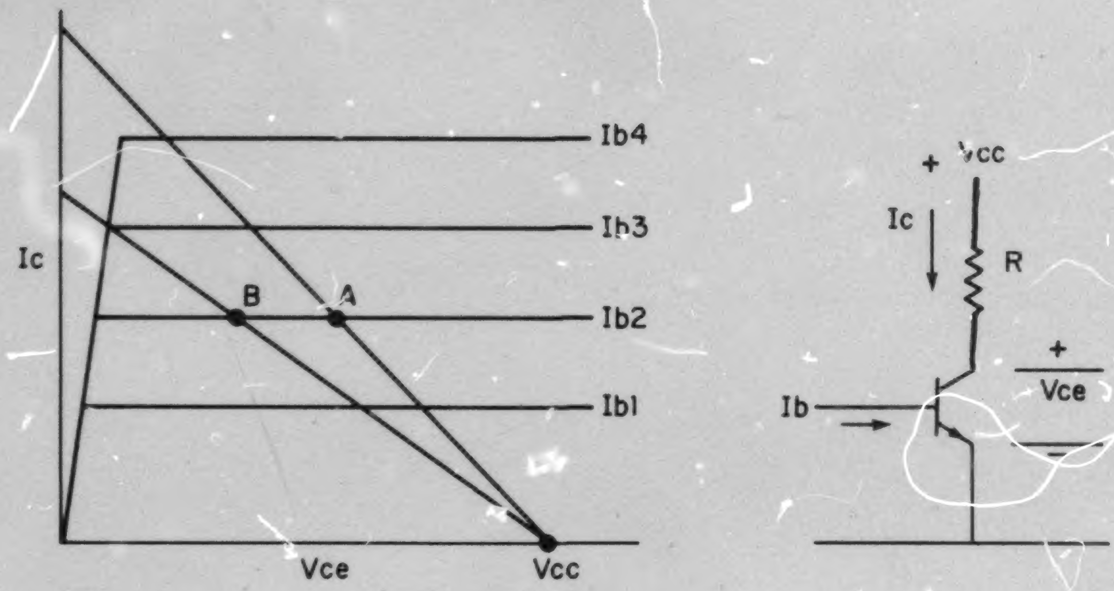
There are several standard ways of explaining such a circuit. The circuit's equations can be written and solved, or a verbal paraphrase of the circuit structure can be given; at best, an incremental analysis may be presented which merely shows that current and voltage relationships are consistent with what the circuit is meant to do.

We think such explanations are rationalizations after the act of design which don't help establish the kind of qualitative, intuitive understanding needed by an expert troubleshooter. We believe a more useful understanding of the circuit is closely allied to understanding the designer's intent when he designed the circuit. Our pedagogical technique, then, is one which describes a hypothetical design for the circuit and its successive refinements.

Complex circuits, in their initial conception, often aren't complex. Usually a simpler initial circuit is proposed; under scrutiny it is discovered to have a shortcoming. This limitation is then "debugged" by adding more components or by changing the circuit's structure. Just as the circuit "evolves" while the designer progressively refines his simpler earlier designs, so can explanations of the circuit proceed in an evolutionary sequence. First we describe *how* the initial simple circuit works, then *why* it fails and *how* a patch was made to rectify the problem. The role of a component in the final version of the circuit can then be understood in terms of a sequence of patches made to an initial (and more easily understandable) circuit. If the initial circuit is understood intuitively and if the way each patch achieves its goal is understood, then the final complex circuit is easily understood and remembered.

The following excerpts from the introductory lesson booklet show the last two steps in such an evolutionary sequence leading to the circuit of Figure 1. The circuit immediately proceeding the final version is established as a current source as a consequence of the transistor's inherent properties:

> ...Fortunately, there are better ways to make current sources. In fact, an ordinary transistor biased as a linear amplifier behaves as a current source for its collector load resistor. This is true because the collector current is determined by the transistor's emitter-base bias, and, *within certain limits*, nothing one does to the collector load resistance can change the collector current.
>
> The reason for this is inherent in the way a transistor works. You probably recall from elementary transistor theory that the collector current is due almost entirely to carriers which have been injected into the base region of a transistor by forward-biasing its emitter-base junction. These carriers have polarity which causes them to be "swept" into the collector circuit by the collector-base bias voltage, and their flow through the collector is what we call the collector current. The collector current is thus controlled only by the biasing of the emitter-base junction. This inherent characteristic of the transistor is shown graphically in Figure 2.



Ideal Transistor Characteristic Curves

Figure 2

The explanation continues by delving into transistor characteristics in some depth...

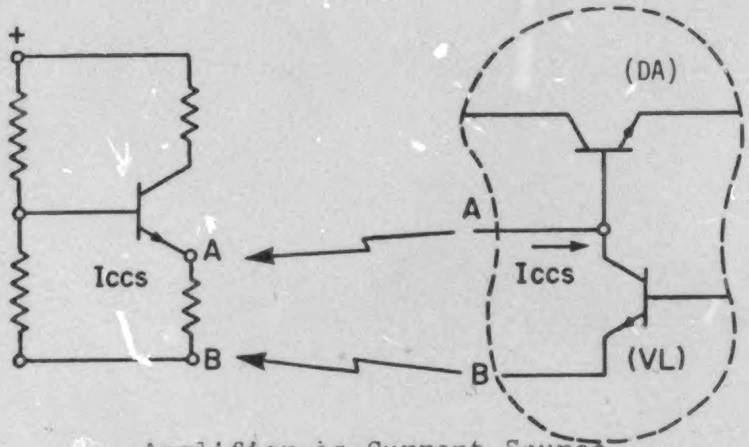
> Figure 2 shows a family of collector characteristic curves for an ideal transistor, as well as the load lines for two different collector resistors. These curves are plots of collector current vs. collector voltage for various values of base current. You'll notice that beyond a certain minimum value of collector voltage, the collector current remains constant with variations of collector voltage for a given value of base current. Now, in Figure 2, you can see the effect of changing the resistance of the collector load resistor. As the resistance increases, the operating point of the transistor shifts from A to B. The current through the resistor thus remains the same while the voltage across it rises.* Earlier we

---

*The voltage across the resistor is the source voltage Vcc minus the collector-emitter voltage Vce.

explained that this is exactly what a resistance "experiences" when driven by a current source; so you can see how a transistor can behave like a current source.

...and reveals a familiar amplifier circuit as a legitimate current source (circuit at left below).



Amplifier as Current Source

Figure 3

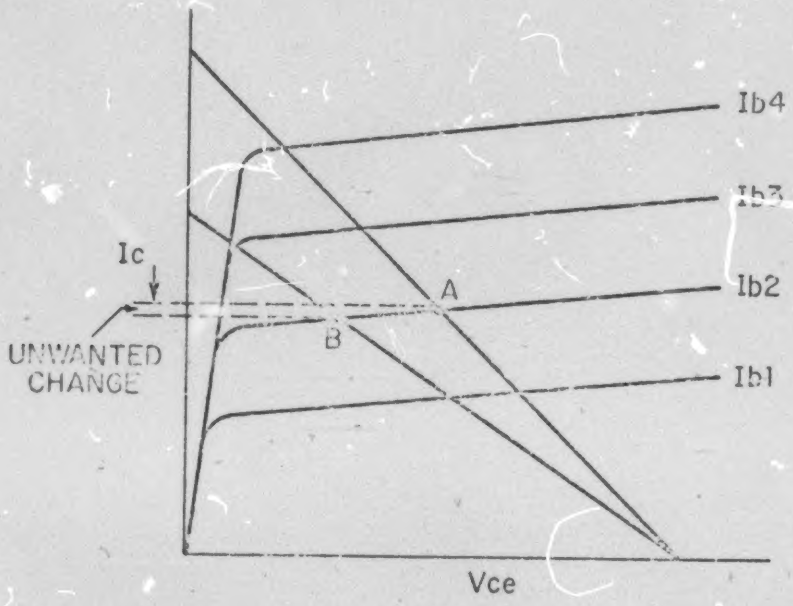
Thus the amplifier shown in Figure 3 will make a good current source for the IP-28 if instead of driving a collector load resistor of A-B as shown, it drives the VL and DA of the regulator.

A shortcoming of the circuit is pointed out...

Unfortunately reality is almost never as neat as our idealizations of it, and the circuit in Figure 3 above still falls short of being a perfect current source. In particular, the collector current does vary somewhat with the load resistance because the change in collector-base voltage caused by large variations of load resistance affects the emitter-base circuit. This effect in turn causes changes in emitter current and consequently in the collector current too.

..and elaborated at some length...

A real transistor therefore generates curves which look more like the ones shown in Figure 4 below. You'll notice that they are not "flat" like those of the "ideal" transistor but tilt upward, showing an increase in collector current with collector voltage. A careful look at the operating points A and B on these curves shows that the current through an associated load resistor decreases slightly as the resistance is increased. Because of this, a real transistor approximates an ideal current source, but doesn't, as you see, quite make it.

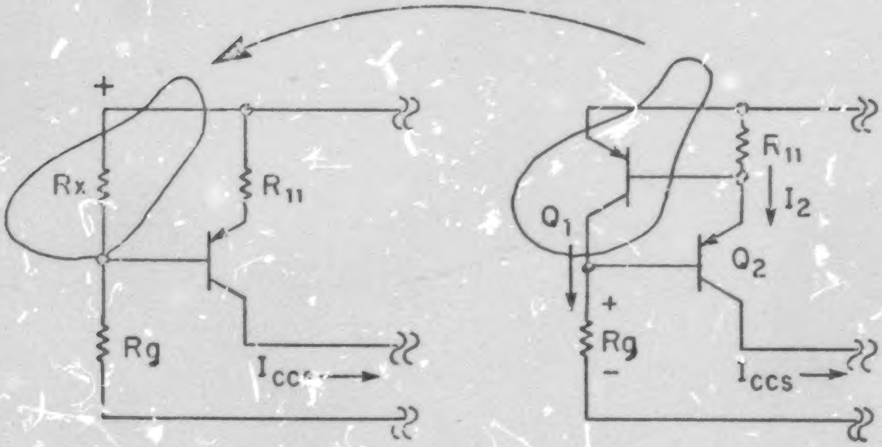


Realistic Characteristic Curves

Figure 4

To rectify the shortcoming, an evolutionary development of the preceding circuit is introduced. Notice below that the complex two transistor circuit no longer appears as complex as it did earlier. Now Q1 is seen, in a sense, as replacing Rx in the divider circuit. It is now the component of the voltage divider which biases Q2 whose role remains identical to the one in the previous design.

To eliminate such "second order" effects, the more complex current source of the actual IP-28 incorporates an additional transistor Q1 which replaces Rx of the simpler source. This is depicted in Figure 5.



Replacing Rx with a transistor

Figure 5

The kind of evolutionary sequence shown above has two interesting properties. First, the sequence depicts a homomorphic chain of successively more complex circuits. By homomorphic we mean that the more complex circuit can be collapsed onto the simpler circuit by replacing a collection of components by a single component (or at least a smaller collection of components), still preserving the underlying structure of the more complicated circuit. Not all design sequences have this property. For instance, the jump from designing a simple constant current source as a resistor (see the instruction booklet for this step which precedes the one we have just illustrated) to designing it as a current amplifier is not a structure preserving operation. Nevertheless, for those evolutionary sequence pairs that are homomorphic, the above description process yields an especially crisp and insightful explanation of how and why a circuit works.

A second thing to notice about this sequence is that it involves just one module in the overall instrument. As is probably obvious, the pedagogical technique we are advocating is recursive. It can equally well apply to the whole instrument as well as to an isolated functional module.

Chapter 3

TROUBLESHOOTING GAME

A pedagogically interesting use of the SOPHIE environment is to support gaming activities which exercise students' troubleshooting skills. The competitive aspect of games provides additional motivation for the students to develop their skills. In this chapter, we shall exemplify the value of gaming activities by presenting one such game -- called the two-team troubleshooting game -- and discussing its pedagogical motivations. We include annotated transcripts of two gaming sessions in order to give the reader a glimpse at the kind of reasoning that is being employed by each team. The first transcript is what each team typed and saw printed at their terminal. The second similarly records the computer interaction, but also includes a transcript of what the team members said to each other in the process of locating the fault. The transcript of the verbal interactions between team members illustrates an interesting protocol gathering technique for studying the fine-grain structure of how people reason in troubleshooting.

Brief Description of the Game

The two-team troubleshooting game is played by two teams, each consisting of two people. Each team has its own terminal and can work at its own pace, waiting for its opponent only when absolutely necessary. The game begins with one team (referred to as the "inserting team") introducing an *arbitrary* fault of their selection into the circuit. They must also set the front panel controls to exhibit an external symptom of the fault. The other team (the "debugging team") must then find the fault by performing a sequence of measurements. Each measurement has a cost which roughly reflects the degree of difficulty in making that measurement in a real instrument. For each measurement the debugging team makes, the inserting team must predict the qualitative outcome of the measurement. The scoring is based on the cost of measurements made by the debugging team, adjusted by the success of the inserting team in predicting the outcome. Thus, it is to the advantage of the inserting team to choose difficult faults but not ones so difficult that their consequences can't be predicted. The debugging team, of course, does its best to isolate the fault with the least expensive sequence of measurements. After each fault, the teams reverse roles, with the second team inserting a fault for the first team to troubleshoot.

Pedagogical Motivation

We designed this game with two instructional goals in mind. First, we wanted a self-motivating activity which promoted cost-effective troubleshooting. Second, we wanted an activity which required the student to exercise his causal and teleological understanding of the device. To do well at this game, requires both types of skills.

Basing the score on the total cost incurred by the debugging team encourages them to minimize the number of measurements they perform. Since the cost of any particular type of measurement can be changed, the scoring algorithm can even be used to control the method of troubleshooting encouraged by the game. At present, the costs of measurements are assigned to stress careful observation of external behavior of the faulted instrument, a powerful troubleshooting strategy. The second goal is met by requiring the inserting team to qualitatively predict the effects of their fault. Since the inserting team is required to set up the front panel controls to manifest a symptom, just selecting a fault requires understanding of the purposes and interactions of the functional modules in the circuit. This understanding is further tested each time they are queried about a quantity measured by the debugging team. The overall effect of the game is that each team must probe its understanding, no matter which side of the game they are currently playing! If they are trying to locate the fault, then they must choose each measurement to tell them as much as possible. If they are choosing the fault, they must consider the set of measurements their opponents might make in the light of their ability to predict the results.

The use of two person teams, instead of individuals playing against each other, turns out to be extremely important. Teams are more adventuresome, more willing to exercise their understanding to its limits. Just in choosing a fault, the team members would argue out the possible ramifications of the proposed fault, often requiring substantial pooling of their information as well as debugging each other's misconceptions. Likewise, with two person team troubleshooting and having to agree on the next best measurement to make, there would be a lot of discussion of what could be deduced from each suggested measurement and why.

An interesting by-product of using two person teams is that it provides a beautifully simple way to get a "window" on the reasoning patterns and knowledge of these individuals. We have often tried to collect protocols of students troubleshooting in order to analyze how a particular person was reasoning. However, asking a subject to verbalize why he is making certain measurements produces, at best, an introspective and somewhat self-conscious interpretation of what he is really thinking, providing us with less than satisfactory information. However, the kinds of discussions or arguments that unfold between the team members provide us with surprisingly detailed information about how they are reasoning.* And it all happens very naturally! Later in this chapter, we provide a complete annotated transcript which illustrates the kinds of information generated by this interchange.

Rules for the Two Team Troubleshooting Game

The following section presents the rules governing both the inserting- and the debugging-teams and describes the scoring algorithm.

Inserting Team

The inserting team must fault the instrument and set the front panel controls subject to the following constraints:

1. The inserted fault must not propagate (cause other components to blow out) under the settings used. If a propagation occurs, the inserting team loses 10 points and must insert a fault again.

2. The inserted fault, under the setting selected, must show an external symptom. If it does not, the inserting team loses 10 points and must try again.

3. The inserting team must predict qualitatively, with respect to a working instrument, whether measurements taken by the opposing team are high, low, or okay.

Debugging Team

The debugging team, given the instrument faulted by the inserting team, must perform measurements on the instrument to determine what is wrong. Measurements have the following costs:

a) An external voltage or current measurement costs 1.
b) An internal voltage measurement costs 2.
c) An internal current measurement costs 4.
d) An internal resistance or power dissipation
   measurement costs 6.

---

*Such an analysis is useful in order to achieve a more structural means of evaluating how much a subject had learned or evaluating how well he was actually performing.

When the debugging team believes they have isolated the faulted component, they attempt to replace it. If they are wrong, their cost is increased by 10 points.

Scoring

The object of the game is to get as many points as possible. However, only the team that inserts the fault obtains any points. (Remember roles are switched at the end of each session!) The inserting team's score is:

$$S = C (R/N) - P$$

where:

C is the cost accumulated by the debugging team,

R is the number of right predictions made by the inserting team,

N is the total number of predictions requested of the inserting team, and

P is the penalty score for insertion errors (see above).

Gaming Scenarios

In order to provide an interactive understanding of how this game is structured and how it appears to the user, we have included an annotated game protocol. This protocol was generated troubleshooting the IP-28 power supply whose schematic and description are contained in Appendix A. Some readers might prefer to skip this rather lengthy protocol and proceed to the following section which provides an annotated, typed transcript of the dialogue that transpired between two team members playing a game. This second transcript contains an excellent example of the skills being exercised in the game.

PROTOCOL OF TWO TEAMS ENGAGED IN A GAMING SCENARIO

INSERTING TEAM'S PROTOCOL

```
MENU CHOICE: GAME
IN ORDER TO ESTABLISH A CONNECTION BETWEEN YOU AND YOUR OPPONENT, IT
IS NECESSARY FOR ONE OF YOU TO INITIATE A SIGNAL AND THE OTHER TO WAIT
FOR IT.  DO YOU WANT TO INITIATE? (YOU MUST KNOW YOUR OPPONENT'S JOB
NUMBER.)
> YES
WHAT IS YOUR  OPPONENT'S JOB NUMBER?
> 7
JOB 7 IS READY.
DO YOU WANT TO INSERT THE FIRST FAULT?
> YES
HOW DO YOU WANT ME TO FAULT THE INSTRUMENT FOR YOUR OPPONENT?
>> LET R22 HAVE THE WRONG VALUE.
IS IT OKAY IF I USE 25 FOR THE VALUE OF R22 ?
> NO
WHAT VALUE SHOULD I USE?
> 8
NOW THE VALUE OF R22 IS 8
```

The inserting team is allowed to fault any part in the instrument and can increase their score by choosing a fault which is difficult to find. However, they are expected to be able to predict the consequences of his fault in two ways. First, they must set up the instrument controls so that the instrument is malfunctioning. It is to their advantage to choose settings which make their fault look like lots of other faults. This encourages them to do careful analysis of the effects of the controls. Second, each time the debugging team makes a measurement, the inserting team will be asked to predict the results of that measurement. This forces them to do analysis on how their fault interacts with all of the functional blocks in the circuit.

```
PLEASE GIVE ME SOME CONTROL SETTINGS WHICH CAUSE YOUR FAULT
TO EXHIBIT SOME EXTERNAL SYMPTOM.
WHAT SHOULD THE CURRENT CONTROL BE?
> 1.0
WHAT SHOULD THE CURRENT RANGE SWITCH BE?
> HIGH
WHAT SHOULD THE LOAD BE?
> 2000
WHAT SHOULD THE VOLTAGE CONTROL BE?
> .8
WHAT SHOULD THE VOLTAGE RANGE SWITCH BE?
> HIGH
```

```
THOSE SETTINGS DON'T SHOW A SYMPTOM.
THE OUTPUT VOLTAGE IS 24.3 VOLTS WHICH IS CORRECT
BECAUSE IN A WORKING CIRCUIT THE OUTPUT VOLTAGE IS 24.3 VOLTS.
YOU GET DOCKED 10 POINTS!
WOULD YOU LIKE TO TRY A DIFFERENT FAULT?
> NO
```

The first settings the inserting team picked didn't show a symptom. They are penalized because the debugging team knows this fact before they even begin troubleshooting. In addition, they are docked 10 points.

```
PLEASE GIVE ME SOME CONTROL SETTINGS WHICH WOULD CAUSE YOUR FAULT
TO EXHIBIT SOME EXTERNAL SYMPTOM.
WHAT SHOULD THE CURRENT CONTROL BE?
> .94
WHAT SHOULD THE CURRENT RANGE SWITCH BE?
> HIGH
WHAT SHOULD THE LOAD BE?
> 30
WHAT SHOULD THE VOLTAGE CONTROL BE?
> 1.0
WHAT SHOULD THE VOLTAGE RANGE SWITCH BE?
> HIGH
THOSE DO SHOW A SYMPTOM.
YOUR OPPONENT IS NOW FINDING THE FAULT.
```

For each measurement the debugging team makes, the inserting team is asked to predict the result. This querying of the inserting team is shown between the long line of dashes and the short one. Then the inserting team is shown what transpired at the debugging team's terminal.

```
-----------------
DO YOU THINK THE OUTPUT VOLTAGE IS HIGH, LOW OR ABOUT RIGHT?
> LOW
THAT'S RIGHT
YOUR SCORE SO FAR IS 1 OUT OF 1
-----
>> WHAT IS THE OUTPUT?
THE OUTPUT VOLTAGE IS 1.86 VOLTS.


-----------------
-----
>> IS THAT CORRECT?
THAT VALUE IS INCORRECT BECAUSE IN A WORKING CIRCUIT
THE OUTPUT VOLTAGE IS 2.93 VOLTS.


-----------------
THE CURRENT CONTROL IS NOW 1.0.
DO YOU THINK THE OUTPUT VOLTAGE IS HIGH, LOW OR ABOUT RIGHT?
```

```
> LOW
THAT'S RIGHT
YOUR SCORE SO FAR IS 2 OUT OF 2
-----
>> WHAT IS THE OUTPUT WHEN THE CC IS 1?
THE OUTPUT VOLTAGE IS 1.83 VOLTS.


-----------------
THE BASE EMITTER VOLTAGE OF Q5 IS HIGH, LOW OR ABOUT RIGHT?
> RIGHT
NO.
THE BASE EMITTER VOLTAGE OF Q5 IS -.28 MILLIVOLTS.
WHICH IS INCORRECT BECAUSE IN A WORKING CIRCUIT
THE BASE EMITTER VOLTAGE OF Q5 IS .532 VOLTS.
YOUR SCORE SO FAR IS 2 OUT OF 3
-----
>> WHAT IS THE BASE EMITTER VOLTAGE OF Q5?
THE BASE EMITTER VOLTAGE OF Q5 IS -.28 MILLIVOLTS.


-----------------
YOUR OPPONENT THOUGHT THERE WAS SOMETHING WRONG WITH Q5
WHICH TURNED OUT TO BE AN UNREASONABLE HYPOTHESIS
-----
>> COULD Q5 BE SHORTED?
NO
```

In the future versions, the inserting team may be queried as to whether or not the debugging team's hypothesis was correct.

```
-----------------
IS THE VOLTAGE ACROSS R7A IS HIGH, LOW OR ABOUT RIGHT?
> RIGHT
THAT'S RIGHT
YOUR SCORE SO FAR IS 3 OUT OF 4
-----
>> WHAT IS THE VOLTAGE ACROSS THE VOLTAGE CONTROL?
THE VOLTAGE ACROSS R7A IS 28.9 VOLTS.

-----------------
DO YOU THINK THE COLLECTOR CURRENT OF Q2 IS HIGH, LOW OR ABOUT RIGHT?
> RIGHT
THAT'S RIGHT
YOUR SCORE SO FAR IS 4 OUT OF 5
-----
>> WHAT IS THE COLLECTOR CURRENT OF Q2?
THE COLLECTOR CURRENT OF Q2 IS -.59 MILLIAMPS.

-----------------
DO YOU THINK THE BASE EMITTER VOLTAGE OF Q3 IS HIGH, LOW OR ABOUT
 RIGHT?
> RIGHT
```

```
THAT'S RIGHT
YOUR SCORE SO FAR IS 5 OUT OF 6
-----
>> WHAT IS THE VBE OF Q3?
THE BASE EMITTER VOLTAGE OF Q3 IS .48 VOLTS.


-----------------
YOUR OPPONENT TRIED TO REPLACE Q3
-----
>> REPLACE Q3
Q3 NOT REPLACED.
```

Here again the inserting team may be queried as to whether or not it was reasonable to replace Q3.

```
-----------------
DO YOU THINK THE CURRENT THRU R22 IS HIGH, LOW OR ABOUT RIGHT?
> HIGH
THAT'S RIGHT
YOUR SCORE SO FAR IS 6 OUT OF 7
-----
>> IS THE CURRENT THRU R22 CORRECT?
THE CURRENT THRU R22 IS 60 MILLIAMPS.
WHICH IS INCORRECT BECAUSE IN A WORKING CIRCUIT
THE CURRENT THRU R22 IS 1.8 MILLIAMPS.

-----------------
>> REPLACE R22
R22 REPLACED
```

The debugging team found the fault in a total cost of 40. The inserting team is given a percentage of this score depending on how well they predicted the consequences of their fault.

```
YOUR OPPONENT FOUND THE FAULT. HIS ACCUMULATED SCORE WAS 4
YOU KNEW 6 OF 7 THE MEASUREMENTS YOUR OPPONENT MADE SO YOU GET
34.3 POINTS.

NOW IT'S YOUR OPPONENT'S TURN TO CHOOSE THE FAULT.
 . . .
```

DEBUGGING TEAM'S PROTOCOL

```
MENU CHOICE: GAME
DO YOU WANT TO INITIATE?
> NO
YOUR OPPONENT IS JOB 32
YOUR OPPONENT IS 'FIXING' THE INSTRUMENT.
```

The debugging team waits for their opponent to fault the instrument and set its controls so that it is exhibiting a symptom.

```
HE HAS CHOSEN A FAULT AND IS SETTING UP THE INSTRUMENT CONTROLS.
HE HAS SET UP THE INSTRUMENT AS FOLLOWS:
CC=1.0, CR=HIGH, LOAD=2000, VC=.8, VR=HIGH
BUT THOSE SETTINGS DON'T EXHIBIT A SYMPTOM SO HE IS TRYING
TO PICK A DIFFERENT SET.
```

The settings which the inserting team picked didn't show a symptom so they have to find some others that do. The debugging team now has the advantage of knowing some settings which don't show a symptom without being charged for it.

```
HE HAS SET UP THE INSTRUMENT AS FOLLOWS:
CC=.94, CR=HIGH, LOAD=30, VC=1.0, VR=HIGH
YOU MAY BEGIN TROUBLE SHOOTING.

>>WHAT IS THE OUTPUT
THE OUTPUT VOLTAGE IS 1.86 VOLTS.
ACCUMULATED COST = 1
```

The debugging team now troubleshoots the instrument with a cost being assigned to each of their measurements. External measurements are cheap.

```
>>IS THAT CORRECT
THAT VALUE IS INCORRECT BECAUSE IN A WORKING CIRCUIT
THE OUTPUT VOLTAGE IS 2.93 VOLTS.
ACCUMULATED COST = 3
```

The debugging team can use a working circuit to make reference measurements but they are charged for it.

```
>>WHAT IS THE OV WHEN THE CC IS 1?
WITH THE CURRENT CONTROL NOW SET TO 1
THE OUTPUT VOLTAGE IS 1.83 VOLTS.
ACCUMULATED COST = 4

>>WHAT IS THE BASE EMITTER VOLTAGE OF Q5
THE BASE EMITTER VOLTAGE OF Q5 IS -.28 MILLIVOLTS.
ACCUMULATED COST = 6
```

Internal measurements are more expensive than external ones.

```
>>COULD Q5 BE SHORTED?
SHOULD Q5 HAVE FAULT MODE EB/EC/BC = SH/SH/SH?
> NO
WHICH TERMINAL SHOULD BE MODELLED OPEN?
> COLLECTOR
OK, I'LL USE EB/EC/BC = SH/OP/OP
WHEN THE SETTINGS WERE:
        CC=1, CR=HIGH, LOAD=30, VC=1.0, VR=HIGH,
THAT FAULT DOES NOT EXPLAIN THE FOLLOWING SYMPTOM.
YOU OBSERVED THAT THE OUTPUT VOLTAGE WAS 1.83 VOLTS.
IF Q5 HAD FAULT MODE EB/EC/BC = SH/OP/OP IT WOULD BE 30 VOLTS.
IN A WORKING CIRCUIT IT IS 29.8 VOLTS.
SHALL I CONTINUE COMMENTING ON YOUR HYPOTHESIS?
> NO
```

At present hypothesis checking is free to encourage the student to present his ideas to SOPHIE for evaluation. In future versions, the student may rewarded for giving correct hypotheses, and charged for incorrect ones.

```
>>WHAT IS THE VOLTAGE ACROSS THE VOLTAGE CONTROL
THE VOLTAGE ACROSS R7A IS 28.9 VOLTS.
ACCUMULATED COST = 8

>>WHAT IS THE COLLECTOR CURRENT OF Q2?
THE COLLECTOR CURRENT OF Q2 IS -.61 MILLIAMPS.
ACCUMULATED COST = 12
```

Internal current measurements are expensive.

```
>>WHAT IS THE VBE OF Q3
THE BASE EMITTER VOLTAGE OF Q3 IS .49 VOLTS.
ACCUMULATED COST = 14

>>REPLACE Q3
I AM GOING TO ASK YOU SOME QUESTIONS ABOUT HOW Q3 IS FAULTED.

ARE ANY JUNCTIONS SHORTED?
> NO
ARE ANY TERMINALS OPEN?
> YES
WHICH TERMINALS ARE OPEN?
> EMITTER
ANY OTHERS?
> NO
THAT'S NOT ACTUALLY WHAT'S WRONG. LET'S SEE IF IT WAS REASONABLE.

UNDER THE SETTINGS:
CC=1, CR=HIGH, LOAD=30, VC=1.0,VR=HIGH
THE FAULT WHICH YOU PROPOSED WILL PROPAGATE.
LIKELY FAULTS WHICH MIGHT OCCUR ARE:
```

```
R22 OPEN

WOULD YOU LIKE ME TO COMMENT ON YOUR HYPOTHESIS AS IF NO OTHER PARTS
HAD BLOWN?
> YES

THAT FAULT AGREES WITH ALL OF THE MEASUREMENTS THAT YOU HAVE TAKEN
UNDER THE PRESENT SETTINGS.
SHALL I CONTINUE COMMENTING ON YOUR HYPOTHESIS?
> NO
Q3 NOT REPLACED.
ACCUMULATED COST = 24

>>IS THE CURRENT THRU R22 CORRECT?
THE CURRENT THRU R22 IS 61 MILLIAMPS WHICH IS INCORRECT
BECAUSE IN A WORKING CIRCUIT THE CURRENT THRU R22 IS 1.8 MILLIAMPS.
ACCUMULATED COST = 30
```

For this question the team is charged for both the internal current measurement and the reference measurement.

```
>>REPLACE R22
IS R22 OPEN OR SHORTED OR DOES IT HAVE THE WRONG VALUE?
> ITS VALUE IS WRONG
IS THE VALUE TOO HIGH OR TOO LOW?
> LOW
R22 REPLACED.
ACCUMULATED COST = 40
```

The debugging team finds the fault, is told the inserting team's score and is given a chance to insert a fault of their own.

```
YOUR TOTAL COST WAS 40
YOUR OPPONENT KNEW WHAT 6 OUT OF 7 OF YOUR MEASUREMENTS WOULD BE
SO HE GETS 34.3 POINTS.
NOW IT'S YOUR TURN TO INSERT A FAULT.
HOW DO YOU WANT ME TO FAULT THE INSTRUMENT FOR YOUR OPPONENT?
 . . .
```

Transcript

Most of the experiments we conducted around the gaming activity were focussed on investigating how best to structure the rules for the game, what its pedagogical benefits were, and how students reacted to it. Therefore, we decided to tape record some of the games.* We have included below a complete annotated transcript of one of these sessions -- one which we think accurately portrays the kinds of involvement typical of all of these sessions.

---

*Since these transcripts had to be synchronized with what was being typed on the computer terminal, we developed a simple technique to record the dialogues and provide automatic synchronization. We used a 4-channel high quality tape recorder. Two channels were used to record team conversations, via microphones placed in the separate work rooms. The remaining two channels recorded the acoustic coupler signals which produced the terminal interactions, thus preserving the exact sequence of events. Because of this recording technique, we can accurately reproduce the entire session, displaying the terminal interaction via acoustic coupler on a terminal while playing the recorded conversations through audio speakers.

```
----------
HE HAS SET UP THE INSTRUMENT AS FOLLOWS:
        CC     .8
        CR     HIGH
        LOAD   10
        VC     .8
        VR     HIGH

YOU MAY BEGIN TROUBLESHOOTING
----------
```

SOPHIE prints settings which opponent has chosen.

J: We are on [VR] high, [CR] high, [VC] .8, [CC] .8 and the load is 10 ohms.

S: Everything is on high, everything else is low.

After getting 'burned' a few times, students are now very careful to note how the instrument is set up. This tells them how it <u>should</u> behave.

J: OK, that means we've got to be in current limiting. Because we've got 30 volts, maybe like 25 volts out and a 10 ohm load, so we will be in current limiting.

A simple use of ohms law tells them that a working IP-28 would be in current limiting mode.

S: OK, we have 10 ohms in the [inaudible] ask for OV. [pause] OK now why do you say that this thing is in current limiting now?

J: You got a 10 ohm load and about 25 volts out.

```
----------
>>WHAT IS THE OV?
THE OUTPUT VOLTAGE IS 6.1 MILLIVOLTS.
ACCUMULATED COST = 1
----------
```

S: OK, the output is 6.1 millivolts. We ought to check to see what the output is of the reference voltage.

Student is stating a hypothesis implicitly: the reference module could be faulted.

```
----------
>>WHAT IS THE V ACROSS C2?
THE VOLTAGE ACROSS C2 IS 28.9 VOLTS.
ACCUMULATED COST = 3
----------
```

J: Ok. Now we want... This thing is in current limiting. OK, yes, because everything is high and the voltage is so low. It's costing us money now. The voltage across C2 is 28.9 volts. It's good!

Minimizing cost is strongly motivated by the game competition. They're excited and involved.

It's good! You know it. [pause]

S: OK. We ought to check, just to isolate things, we ought to... it might be worthwhile to check out the output current [of the Constant Current Source]. If this output current...

Discussion of alternative measurements - cost vs. benefit.

J: I was thinking of checking the voltage [at N4]. It's cheaper.

S: We know this is a constant current source. We know what the current has to be, but we don't know where it's going... We don't know what the voltage is, though.

J: We could tell if it is very low.

S: How can you tell?

J: It is supposed to be 23 volts. I think. Something like that. 24 volts.

Students debugging each other's models of the circuit.

S: The thing varies. On some loads it's 30.6 volts and on some loads it's 23 volts. Like for instance, they had this thing set at .8...

"Peer teaching" helps both parties.

J: The thing is, Steve. I don't want to use current measurements until the very end! Current measurements cost money. You make current measurements when you're sure you have found the section at fault.

This shows how the differential (and realistic) costs of measurements impact thinking.

S: If we make this current measurement here [output current of CCS], it's going to tell us if this voltage measurement here [at N1] is OK or not. Up here at the output of the DCS. You see my point? That way we are making a voltage measurement and a current measurement. A current measurement is telling us if this thing here is OK here [voltage at N1].

Here is an inference step which the student has invented - the Expert Debugger does not use it!

J: OK. Go head, but it's going to cost money.

S: But, OK, let's say that this [voltage at N4] is at 15 volts. You might argue that that's high and I might argue that's low.

Student points out that measurements for which you have no norm are of little value.

J: OK, let's do the current measurement.

S: We know it has to be .6 [milliamps].

So the more useful, though more costly measurement is made.

J: IQ2.

```
----------
>>WHAT IS THE IC OF Q2?
THE COLLECTOR CURRENT OF Q2 IS -.61 MILLIAMPS.
ACCUMULATED COST = 7.
----------
```

S: OK. It's good.

J: OK, now we have to figure out where that current is going to. There's two ways we could figure it out. We can take V [of Q6] and V [of Q5] and see which one is drawing all the current. Let's see what the output voltage should be on this thing. Oh, we can't tell dammit.

Using Kirchoff's law: the current must be going somewhere.

S: But we know that it shouldn't be 6.1 millivolts.

J: You talking about the output voltage?

S: Yeah.

J: You mean right here.

S: Yeah.

J: OK, we know it can't be 6.1 millivolts because this [the output of Vref] is 28.9 volts. The reference voltage. The reference voltage and the output voltage should be the same.

This teleological statement is wrong, missing two caveats: There is an offset and even so, the relation is only when not current limiting as it is here. This error doesn't hurt them this time...

S: Let's take those two voltage measurements.

J: Before we take it, what's that going to accomplish?

An Excellent example of a "rational" or "non-rote" approach to troubleshooting.

S: If we take the voltage measurement across Q6, we will know if Q6 is conducting very heavily. And the same thing goes for Q5. If the voltage is low it means that it is conducting heavily.

Again, a caveat is unstated.

J: It's definitely in current or voltage limiting. One of these two paths is taking the current away from here. OK. One of those two paths. Almost definitely. It's most likely one of these two paths. One of these two paths more than likely is taking the current away. And we can find out by measuring the voltage drop here [Vce Q6] and voltage drop [Vce Q5].

Teleological knowledge based on Kirchoff's law (above).

S: OK. Right there aren't you assuming that this Darlington pair is dropping all the voltage? If this is 6.2 milliamps, I am going to assume that it's 50 volts right here [at N1].

J: Yes, that is reasonable.

S: OK, you want to check the voltage at N5 and see if the Darlington pair is dropping all the voltage?

J: Definitely, definitely. No doubt in my mind at all. I don't even think that it's worth measuring.

Avoiding a useless measurement.

S: It isn't worth measuring?

J: Nope. It has to be, Steve.

Interesting team interaction.

S: What?

J: It has to be dropping all the voltage. One of these two paths has taken the current away.

S: What happens like for instance if this thing is dropping no voltage and what it is is that this resistor right here [R16] is open? What happens then? By your logic it is going to be giving us the same indication there.

Alternate hypothesis which explains observed symptoms.

J: OK. If that's true, then there'd be no bias. Oh, yes. There would be bias. OK, you want to measure that. Let's measure it, what the hell. We only got 7 [points] here. [inaudible]

```
----------
>>V AT N5
THE VOLTAGE AT N5 IS 6.0 MILLIVOLTS.
ACCUMULATED COST = 9.
----------
```

J: Ok so, it isn't being dropped across there.

Alternate hypothesis is eliminated by a single measurement.

S: So we don't even have to bother to look over in this area then. VCE Q6.

J: OK, all the voltage is being dropped [across] the Darlington pair there. OK. Why don't we just write down exactly just what could cause these symptoms. OK, the first thing is that DA is open.

New plan: Enumerate remaining possibilities (per the Expert!).

Hypothesis I

S: DA?

J: DA. Darlington, you know the block DA. DA is open.

Hypothesis II

S: Q6 conducting heavily. Q5 conducting heavily.

Hypothesis III

J: Well, if you had Q6 conducting heavily, I would think that that can't be the situation because you would probably have .6 milliamps times 10 ohms which will give us about 6.1 millivolts.

Discussion of Hypothesis II.

S: Times 10 ohms?

J: Yeah. I mean that would, hey wow!! That's a real good bet. Because look at this:

S: .6 milliamps times 10 ohms gives you 6.2 millivolts. You're right, you're right. There might be a direct short right there. Or right there, that would be it. V Q6.

J: OK. This could be the baby!

S: Yeah. V Q6. V Q6.

An exciting thing has happened: The students have discovered a fact of which we were unaware, despite intimate familiarity with the instrument! For this and similar faults, the only current arriving at the output is coming from the constant current source! Students have good reason to be excited.

```
----------
>>VCE Q6
THE  COLLECTOR  EMITTER  VOLTAGE  OF  Q6  IS   .13
MILLIVOLTS.
ACCUMULATED COST = 11.
----------
```

J: Well, baby! That looks like .13 millivolts. I mean that thing isn't even shorted out. I mean that thing isn't saturated because saturated would give us .4 volts.

S: Right.

J: The thing is shorted out. We have got the problem, baby!

It must be Hypothesis II.

S: That's right, it would have to be at least .6 volts, wouldn't there? Replace Q6. I'm game.

J: I'm game too, but OK now...

S: Let's take one more thing. That won't prove anything, will it?

J: I mean we have already... I mean it is physically impossible for that transistor to be operating correctly and to have that voltage across it.

Student overstates meaning of last measurement,

S: Well, the other possibility is that the voltage just isn't available in the first place. OK?

And is corrected by his partner: a good point.

J: Oh, I see what you mean. But it is available...

S: If there was a short right here.

J: No it is available. Ok, we know here that (there's no ground here, is it?) there is a wire running down like this. If you had a short here, Steve, there wouldn't be any voltage available here.

S: But don't forget that at this point here [at output] we have 6.1 millivolts.

J: Where is 6.1 millivolts?

S: See. 6.1 millivolts. See you have 6.2 millivolts here [at output] and it drops about .1 millivolts through there [Q6].

J: OK, so it's 6.1 millivolts there and if this was shorted right here we could still do that. We could ask for IC Q6. Just to be safe. I would rather take the four extra points than to replace the wrong component.

An attack of caution.

S: OK, I see what you mean. OK, now I Q6. You say that it could be shorted. Let's just say that it is shorted right to ground. You are going to have a ground potential at this point...

J: You would have the same thing, like a real low voltage, just the lead resistance of the same thing, like this .13 millivolts.

S: OK, let's say that it could be like 5.9 millivolts and the difference between the two could be .13 millivolts. I see what you mean. It's definitely a point there. But now if we were to check I Q6.

Discuss what measurement would make them absolutely sure.

J: And found that to be .6 milliamps, we got it.

S: I would rather do that than to replace it. [inaudible]

J: You're right. I Q6.

```
----------
>>IC Q6
THE COLLECTOR CURRENT OF Q6 IS .6 MILLIAMPS.
ACCUMULATED COST = 15.
----------
```

They perform the confirming measurement, S: Oh, we should have replaced it! Replace Q6.

And realize their over-caution.

```
----------
>>REPLACE Q6
I AM GOING TO ASK YOU SOME QUESTIONS ABOUT HOW  Q6
IS FAULTED.
----------
```

S: It's going to ask some questions.

SOPHIE asks for detailed fault mode.

```
----------
IF AT ANY TIME YOU WOULD LIKE TO MAKE MORE
MEASUREMENTS, SIMPLY TYPE CONTROL-E.
ARE ANY JUNCTIONS SHORTED?
>YES
WHICH ONES?
>EMITTER TO COLLECTOR
ANY OTHERS SHORTED?
>NO
THE COMPLETE FAULT MODE WAS THAT Q6 HAD ITS
EMITTER COLLECTOR JUNCTION SHORTED AND ITS BASE
OPEN.
Q6 REPLACED.
ACCUMULATED COST = 18
WAITING FOR WORD FROM OTHER PLAYER.
----------
```

They had the exact fault mode. (SOPHIE would have allowed them to be wrong about the base.)

J: It doesn't matter. It won't hurt our score. OK. But we know this thing only accepts it. Base open. Wow that was cheap. We did good, man, we did good.

S: 18 baby, we are gooood! [repeated several times]

A little gloating is in order.

J: We should have had 15.

S: I think it was worth the 3 points.

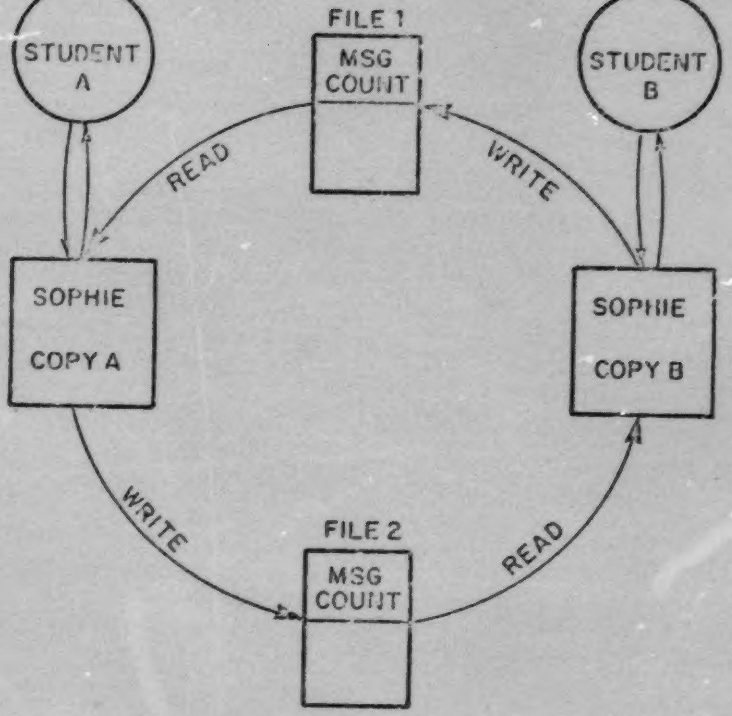
J: I think so to, actually, because there was a possibility that it could have been Q5 short.

Technical Details

Before discussing some of the implementation details of the two-team troubleshooting game, it is worth noting that much of the pedagogical leverage of this game stems from SOPHIE's use of a general purpose circuit simulator. Unlike many training "simulators" which faithfully simulate the outer appearance of a device but which rely on only a finite set of tables to "simulate" its internal behavior, SOPHIE has, in effect, an infinite set of tables, any one of which it can generate on the fly. This means that SOPHIE is not limited to handling only a pre-determined set of faults or measurement ports. This flexibility is crucial in the game, for without it each team would be restricted to pre-determined faults. (Troubleshooting would then become more like that of finding out which of a (small) predetermined set of possibilities is in fact the selected fault.) Furthermore, the challenge of dreaming up unusual and potentially pathological faults would be all but eliminated, resulting in a much less challenging gaming environment.

During a game, one team is debugging the instrument and the other team is being quizzed about the debugger's measurements. To implement this within the SOPHIE environment required only the following changes: the normal SOPHIE executive routine was rewritten so that, when playing a game, it sends the semantic forms of all the debugging team's statements to the inserting team's version of SOPHIE. The inserting team uses a new executive which reads a semantic form from the communication file, quizzes the inserting team about it (if necessary) and executes it in the inserting team's system so that they are aware of the debuggers' context. In addition, the gaming situations require routines to keep track of both teams' scores, to ask for a fault and settings and determine if they exhibit symptoms, and to switch roles at the end of the game.

The communication link between two teams in a gaming scenario is established via files. Each team has its own copy of SOPHIE (running as its own process), so that each team works at its own pace and only has to wait for the opponents when absolutely necessary. The situation is shown in Figure 1.


STUDENT A
FILE 1
MSG COUNT
STUDENT B
READ
WRITE
SOPHIE COPY A
SOPHIE COPY B
WRITE
READ
FILE 2
MSG COUNT

Communication Between Two Copies of SOPHIE

FIGURE 1

Chapter 4

EXPERT DEBUGGING INTERACTION

The expert debugging interaction was designed to complement SOPHIE lab activity. It had been our experience that beginning SOPHIE users needed a lot of prompting in order to make good use of the full range of lab facilities. We sought an activity which would provide a gradual path towards full use of the SOPHIE lab, and which would explain debugging strategy to students.

To this end, the Expert Debugger was implemented. The Expert is a program which is able to diagnose faults in the IP-28 power supply at a function-block level. More significantly, it is able to explain its logic, its hypotheses, and its conclusions as the debugging proceeds. To the student user, it appears as an experienced, thoughtful and articulate expert. The interaction is made more engaging by having the student predict, in a qualitative way, how the faulted instrument behaves.

This chapter discusses the expert debugging interaction in terms of its educational motivations and impact, and debugging strategy. It also provides a detailed description of the interaction and an annotated sample run.

Educational Rationale

There are several pedagogical reasons for conducting the Expert Debugging Dialog. First, the Expert views the instrument at a high level -- in terms of distinct boxes which interact in known ways. In other words, the Expert has a high-level teleological model of how the IP-28 works. Without having to make measurements within functional blocks, the Expert is able to determine which block contains the fault. Whereas this functional approach is only one of many possible debugging methods, it encompasses much of the teleology of the instrument, and is methodical and explicable. The student who develops a personal debugging strategy which proceeds from external symptoms, through meaningful internal blocks, down to the component level will have an approach which will work for most of the faults in the instrument.

A second reason for doing the expert debugging interaction is that it provides practice making predictions of the consequences of faults. The ability to make such predictions is valuable indeed, because it allows one to evaluate one's own hypotheses of faults in the instrument. For instance, if I suspect that the current limiter is always conducting, I must be able to predict the consequences of this fault to see whether they match the symptoms which I observe in the actual instrument. Then, even if I don't know which faults are the most likely, I will be able to use existing symptoms to check out a variety of possibilities in my head. One goal of the Expert interaction is thus to help students become better at proposing and checking their own hypotheses.

A final pedagogical motivation for using the Expert is as a gentle introduction to the SOPHIE lab. When the student makes an erroneous prediction, the program shows him a SOPHIE interaction which discovers the correct answer. Thus, a beginning student is exposed to a variety of questions which he might use later in the SOPHIE lab interaction. He is shown how questions as he might conceive them can be translated into measurements in the instrument. When isolating the actual component fault within the faulted block, the student has a well-defined and relatively easy task to perform in the SOPHIE lab, compared to debugging the whole instrument.

Evolving Models

One way of viewing the process of learning how to debug an instrument is in terms of moving from static to dynamic models. A student may start out with an understanding of the power supply which could be summarized by a simple statement of intent: "The supply puts out a fixed voltage." This model contains no variables, and is thus essentially static. A more refined model contains provision for one contingency: "The supply puts out a fixed voltage, unless its current limit is exceeded, in which case it puts out less." The model develops to encompass internal parts and more interactions. "The power supply puts out a voltage equal to the reference voltage, unless..." And so on. More and more variables are added as the understanding of the power supply improves.

Mechanisms are required for pointing out to students ways in which their developing models do not match the real-world situation. Conflicts of model with fact are the raw material of which better models are made. The expert debugging interaction provides many small opportunities of this sort for students to improve their understanding. Every time a student makes a wrong prediction, he has an opportunity to go through a "What? That can't be! Aha!" cycle which improves the accuracy of his world view. Other opportunities also arise in the SOPHIE environment -- in the lesson material, debugging activities, two-team games, and so on. Nonetheless, the Expert scenarios are particularly rich in this respect.

In order for such conflicts to be used, however, they must be perceived by the student. This is one reason why we chose to alternate Lab and Expert activities. Either alone, while useful, is less effective than the combination. This is because troubleshooting provides not just motivation but a set of experiences with unexplained elements. When similar situations arise for the Expert, the explanation is at once more concrete and digestible. Conversely, things which concern the Expert -- reasons for inferences, caveats, and the like -- which may well not be assimilated on first reading, may make sense later in a debugging problem which can be solved by appeal to them.

Expert Debugging Strategies

The debugging tree used to implement the Expert is only one of many which might have been employed. Its important characteristics are that it operates at a function-block level, relies on only qualitative measurements, contains multiple strategies, and makes only measurements which are teleologically significant. These qualities will be taken up below, each in turn.

There are several reasons for operating at a function-block level. Doing so promotes a basic analytic approach to the instrument: without some decomposition, it would be very hard to understand. Nonetheless, most inexperienced troubleshooters tend to jump in cold, testing at a very local level. In a circuit of even moderate complexity, such an approach will more often than not lead to wasted time and components and may never locate the fault. Thus, a higher level approach is desirable -- one which takes into consideration the intent of collections of components and which establishes expectations to compare with measurements. A block-wise model of the instrument is a convenient mental shorthand for grouping collections of components so that behavioral predictions are easier.

The debugging strategies used rely only upon qualitative measurements. Therefore, the student only needs to make qualitative predictions about the functioning of his faulted instrument. Although such an approach will not isolate faults in all situations in all instruments, it is useful for many. The sort of causal reasoning promoted by this qualitative approach flexes the students' logical muscles. Chains of the sort "Well, this is too high, so this must be too high, and this, therefore, too low..." or "If this goes down, then that must go up..." are important tools. Such chains may need to extend through several steps in circuits which employ feedback or multiple stages. Additionally, qualitative measures fit in well with the level of explanation we deemed appropriate for the Expert to make. We did not want to present many arguments which depended on the actual values of measurements in the circuit, because we felt that to do so would be unrealistic in situations where the instrument to be repaired is new to the troubleshooter. Extensive experience with a particular instrument may in fact yield rules like "If the output voltage is between 33 and 35 volts, replace D5." Such rules, while perhaps valid for repair of familiar equipment by average troubleshooters, do not teach much at a conceptual level. They do not generalize easily to other situations.

Our Expert is not committed to any single strategy, but rather, has several. For example, if the output voltage is high under light load, the Expert will adopt one of two alternate top-level strategies:

A. Extract as much information as possible from observations of the instrument under different settings and load, before proceeding to internal measurements, if necessary.

B. Make measurements which reflect on the workings of the voltage limiter and voltage reference, since these are two modules which could give rise to a high output voltage.

Both approaches have validity. By including both, we expose a student debugger to alternative ways of approaching the problem. One or the other may not make sense to him or may not suit him for some reason. Thus he has a choice of which to adopt for his own use and is stimulated to develop methods with which he is comfortable. At the same time, he is exposed to logic which may make sense to him at a later date. And, he witnesses an expert that is flexible enough to use various strategies at different times.

Finally, and most importantly, our strategies were developed to have measurements which were teleologically significant. This means that each measurement is based in some function-related differentiation of blocks within the instrument. Although there are in principle arbitrarily many possible sequences of measurements (decision trees), what is essential is that we have ruled out tests which cannot be justified clearly in terms of function-block interactions within the instrument.

Hypothesis-Space Splitting

There is, nonetheless, a general sort of strategy which the Expert employs -- that of hypothesis-space splitting. Simply stated, this just means that each measurement is intended to reduce the range of possible faults which would explain the symptoms observed so far. This idea may not seem particularly profound, and it is not. The significant point is that the Expert carries along several competing hypotheses simultaneously. Instead of proposing a single fault and performing a test to shed light on it, the Expert consistently mentions several possibilities which a given test is to help sort out. This is the method of strong inference, as it is called in science, and is much more powerful than attempting to prove or disprove a single hypothesis at a time. Students adopting such a strategy are apt to be significantly better troubleshooters than those who don't. This method is the reason that the Expert is able to localize most faults in three or four tests.

The Expert also evidences a certain degree of planning once a local strategy has been selected. For example, it is desirable to check out the current limiter in the power supply before applying a heavy load. Failure to do so may result in additional components failing before the primary failure is diagnosed. Such considerations argue for extra tests or for performing a given set of tests in a particular order, other things being equal.

Detailed Description of the Interaction

The interaction is actually a trialog. In addition to the student and the Expert, there is a third party called the Demon. The Demon program is responsible for inserting faults to the student's specifications and verifying the student's predictions.

The interaction proceeds as follows: The Expert first explains how the lesson is to proceed -- the Expert is going to try to isolate a faulted functional block selected by the student. Since the student will know what is wrong with the instrument (at a block level), he will be asked to predict qualitatively the results of measurements which the Expert wants to make.

Next, the Demon speaks, asking which block is to be faulted. The student may select any of the seven functional blocks in the IP-28. Depending on which block is selected, the Demon may ask for more specific information about how to fault the block. Except in the case of the output filter (OPF), which has only two components, the student will know only the external behavior of the faulted block, not the actual component fault. Thus, his predictions will be based on a qualitative statement of how the faulted block behaves. The Demon only selects faults which have clear qualitative symptoms which the student should be able to propagate through the instrument, making the predictions which the Expert requests. After the student has made his selection, the Demon restates the fault in terms of the qualitative behavior at the faulted block.

Next, the Expert attempts to locate the fault, explaining his strategy as he goes. For each measurement he wants, the student is queried as to the qualitative behavior of the instrument in the area in question. Depending on the particular approach taken by the Expert, it may ask the student a question or two about what can be determined from the measurements made up to that point, commenting on his response.

If the student makes a wrong prediction, the Demon takes over to demonstrate the actual behavior of the faulted instrument. He does this by posing a SOPHIE lab question which will resolve the issue. SOPHIE responds with an actual measurement, and the Demon restates the measurement qualitatively, in terms of the Expert's question.

If the student doesn't know the answer to one of the Expert's questions, he may ask for help. The Demon will ask SOPHIE, as above, and summarize the answer. The student is not penalized for asking for help.

When the Expert has decided what block contains the fault, he announces this to the student, along with the final bit of logic which led to the conclusion. The student is asked whether the conclusion is correct, and whether he would like to isolate the actual component fault. If the answer to this latter question is 'yes,' a summary of the Expert's measurements (expressed as answers to SOPHIE lab inquiries) is printed, and the student is put into a SOPHIE lab environment with the faulted instrument and an appropriate history list. He may take any measurements he wishes, evaluate hypotheses, and so on, as in a normal lab session. What follows is an annotated sample of the expert debugging interaction.

SAMPLE EXPERT DEBUGGING INTERACTION

```
What is your name?
> DICK R

Welcome to SOPHIE - a simulated electronics
laboratory - which has on-call a tutor and an
expert debugger.

The choices are:
A  Short prologue
B  Long prologue
C  SOPHIE lab
E  Interact with expert debugging
F  STOP
G  Two person debugging game

Menu choice: E
```

Student selects functional debugging.

```
EXPERT:
For this session, we will work at a function-block
level with the IP-28.  I am going to try to
isolate the faulted block which you choose.  Since
you will know what block is faulted, I will ask
you to predict the circuit's behavior.  I hope to
find out which block contains the fault.  If at
any time you are unable to answer one of my
questions, feel free to type HELP and I will give
you some assistance.

From time to time, I may ask you a question about
my progress at finding the fault.

DEMON:
For this session, I need a fault specified by a
functional block.  Which block do you want to have
the fault? (DCS, CCS, DARL, VL, CL, OPF, or Vref)
```

Procedure for the game.

```
DICK: VOLTAGE LIMITER
```

Student selects a block.

```
DEMON:
I will insert a fault which makes the VL always
conduct.
```

Qualitative restatement of how block will behave.

```
EXPERT:
OK.  Here we go.  Before delving deeply into the
instrument I am going to make simple external
measurements.  The simplest and most obvious
measurement to make at first is to check the
output voltage.  However, I would also like to be
clear about how the instrument is set up.The
settings I will use initially will be the
```

The Expert always observes external symptoms first, in order to verify that the instrument is malfunctioning and to get some inexpensive information about the fault.

following; CC=1.0, VC=1.0, LOAD=1000, CR=HIGH, VR=HIGH. Notice that under these settings, the instrument is adjusted to deliver its maximum voltage. In addition, the load is a moderate 1000 ohms so that the current demanded from the supply is a mere 30 ma. This is well below the current limit setting (1 ampere) and, consequently, the instrument (if properly working) should be working in its voltage limiting mode. Now I will make the first measurement.

The Expert discusses the state of a working instrument because it establishes expectations for internal and external measurements which can be compared with those in the faulted instrument.

Here is how the instrument is set up...

SETTINGS:

CC	1.0
CR	HIGH
LOAD	1000
VC	1.0
VR	HIGH

How does the OUTPUT VOLTAGE compare with a working circuit?

DICK: LOW

EXPERT:
Every functional block has a failure mode which could cause the output to be low under these conditions, so I need some more information.

The Expert knows of faults in every block which cause low output, the only symptom so far.

Is the OUTPUT VOLTAGE essentially zero?

The Expert asks for a more refined, although still qualitative prediction about the output.

DICK: YES

EXPERT:
AH GOOD! That is important information for me because I don't suspect the Vref now. If the Vref were dead, that is, had no output whatsoever, then the output voltage would still be around one and one half volts. It would have this magnitude because the voltage limiter cannot even begin to function until its input voltage rises above the junction voltage drop of its input transistor. And, of course, if Vref had any voltage output greater than zero, the output voltage would be still greater. Having eliminated the Vref, I now wonder about the CL, VL, DARL, CCS and OPF. Any one of these could cause the output voltage to be zero so I am going to narrow the search.

An instance of teleological knowledge at a block level: failures in Vref cannot make the output essentially zero. This is a somewhat surprising fact which the student may want to verify experimentally in the SOPHIE lab.

How does the VOLTAGE AT N1 compare with a working circuit?

Although this test is aimed primarily at only one block, it is nonetheless desirable because the rest of the blocks cannot function unless this block is working.

DICK: OK

EXPERT:
So the DCS is not faulted. The remaining blocks which are now suspect are the CCS, DA, CL, VL, and OPF. I think I will check the CCS now since it is at the heart of the regulating mechanism of the supply and since it has the least interaction with all the other blocks.

How does the OUTPUT CURRENT OF THE CONSTANT CURRENT SOURCE compare with a working circuit?

A similar sort of test, but with a more elaborate interpretation. It can verify that the block is OK, but cannot alone prove that it is bad.

DICK: OK

EXPERT:
The current source is working then. The modules now left are the CL, VL, OPF and DARL. I think I will make my next measurement on the Darlington amplifier.

Three of the seven blocks have already been eliminated.

I want to know whether the BASE CURRENT OF Q4 is OK.

This test will split the hypothesis space, eliminating two blocks in either event.

DICK: HELP

Student doesn't know the answer and requests assistance.

EXPERT:
Let's use SOPHIE to find the answer:

```
----------
>>IS THE BASE CURRENT OF Q4 OK

THE BASE CURRENT OF Q4 IS 0.0 AMPS.
WHICH SEEMS TO BE INCORRECT BECAUSE IN A WORKING
 CIRCUIT IT IS .031 MILLIAMPS.

----------
```

What is shown is a real SOPHIE lab interaction which answers the Expert's question.

So you see that the BASE CURRENT OF Q4 is LOW in the faulted circuit.

Paraphrase of answer in terms of the Expert's original question.

Let's go on...

EXPERT:
Low input current to the Darlington amplifier would certainly result in lower than normal voltage at this output under moderate current loads. I think then, the Darlington amplifier is OK, since it is following its input. Now, since we have already seen that the CCS output current is OK, perhaps either the current limiter or the voltage limiter must be drawing excessive current from the CCS.

A practical instantiation of a theoretical relationship called Kirchoff's current law.

Is Q6 conducting?

DICK: YES

Only two possibilities remain. This test will differentiate between them.

DEMON:
SOPHIE tells me that your prediction isn't right:

But the student has predicted wrong.

```
----------
>>WHAT IS THE COLLECTOR CURRENT OF Q6
THE COLLECTOR CURRENT OF Q6 IS 0.0 AMPS.

----------
```

The Demon steps in to demonstrate that the student has erred, using the SOPHIE lab.

Thus I conclude that Q6 is not conducting.

Let's go on...

EXPERT:
At the last measurement, I had arrived at the conclusion that either the CL or VL was drawing excessive current away from the CCS. As you can see from the present measurement, the CL collector current is zero. It is not the CL then which is drawing the current. That leaves the VL as the only module under suspicion. It has to be faulted with a short. You faulted the VL.

Only one possibility remains, and no confirming measurement is taken. Students often do take final confirming measurements. An example is shown in the gaming transcript in Chapter 3.

Am I right?
DICK: YES
EXPERT:
I'm glad...

Would you like to isolate the actual component fault?

DICK: YES

OK, here is a review of the measurements made so far:

Students may do this activity as a first exposure to the SOPHIE lab.

```
      CC=1.0, CR=HIGH, LOAD=1000, VC=1.0, VR=HIGH,

THE OUTPUT VOLTAGE IS -2.3 MILLIVOLTS.
THE OUTPUT VOLTAGE IS -2.3 MILLIVOLTS.
THE VOLTAGE AT N1 IS 49.3 VOLTS.
THE OUTPUT CURRENT OF THE CONSTANT CURRENT SOURCE
 IS -.61 MILLIAMPS.
THE BASE CURRENT OF Q4 IS 0.0 AMPS.
THE COLLECTOR CURRENT OF Q6 IS 0.0 AMPS.
```

Review of the Expert's measurements in terms of SOPHIE lab replies. These measurements constitute the student's history list at this point.

Go ahead and locate the faulty component:

```
>>WHAT IS THE COLLECTOR CURRENT OF Q5?
THE COLLECTOR CURRENT OF Q5 IS .62 MILLIAMPS.
```

Student checks for the "most likely" possibility, and finds the fault.

```
>>REPLACE Q5
I AM GOING TO ASK YOU SOME QUESTIONS ABOUT HOW Q5
 IS FAULTED.
```

He is queried to insure that he understands the fault made, as in normal SOPHIE lab.

```
IF AT ANY TIME YOU WOULD LIKE TO MAKE MORE
 MEASUREMENTS, SIMPLY TYPE CONTROL-E.
ARE ANY JUNCTIONS SHORTED?
> Y
WHICH JUNCTIONS ARE SHORTED?
> ALL
THE COMPLETE FAULT MODE WAS THAT Q5 HAD ITS
 EMITTER COLLECTOR JUNCTION SHORTED AND ITS BASE
 OPEN
Q5 REPLACED.
```

Q5 was indeed the fault,

```
Now you should take measurements to see  if  there
is anything else wrong with the circuit.
ACCUMULATED COST = 24

>>WHAT IS THE OUTPUT VOLTAGE?
THE OUTPUT VOLTAGE IS 30.1 VOLTS.
```

As a correct output voltage indicates.

```
>>STOP

A  Short prologue
B  Long prologue
C  SOPHIE lab
E  Interact with expert debugging
F  STOP
G  Two person debugging game

Menu choice: INTERACT
```

Another session with the Expert.

```
EXPERT:
For this session, we will work at a function-block
level  with  the  IP-28.  I  am  going  to try to
isolate the faulted block which you choose.  Since
you  will  know  what block is faulted, I will ask
you to predict the circuit's behavior.  I hope  to
find  out  which  block contains the fault.  If at
any time you  are  unable  to  answer  one  of  my
questions,  feel free to type HELP and I will give
you some assistance.

From time to time, I may ask you a question  about
my progress at finding the fault.
```

Sometimes the Expert may ask a tutorial question.

```
DEMON:
For this session, I need a fault  specified  by  a
functional block.  Which block do you want to have
```

the fault? (DCS, CCS, DARL, VL, CL, OPF, or Vref)

DICK: VREF

Should the output of VREF be high, low, or zero?
DICK: HIGH

Some blocks have a wide enough range of symptoms that the Demon allows the student to choose among them.

DEMON:
Good. I will insert a fault which makes the output of Vref high.

EXPERT:
Back at the beginning... Remember I am making my first measurement under standard settings. The voltage and current controls are set for maximum at the supply's highest ranges. The load is 1000 ohms. A working instrument would operate in its voltage limiting mode under these settings.

Expert presents an alternate text, reminding the student of the expectations expressed at the beginning of his first run.

Here is how the instrument is set up...

SETTINGS:

CC	1.0
CR	HIGH
LOAD	1000
VC	1.0
VR	HIGH

How does the OUTPUT VOLTAGE compare with a working circuit?

DICK: HIGH

EXPERT:
Too high. Hmmm. That means that the output of the Darlington Amplifier is too high for some reason. The problem could be the amplifier itself, or in something that affects its input.

What function blocks might account for the symptom of output voltage too high with these settings?

A tutorial question which attempts to get the student to think of faults which might give symptoms the same as his does for the measurement made so far.

DICK: DCS AND VREF

EXPERT:
I don't really suspect the DC Source. Remember that the output is too high. Even if the output of the DCS were too high, the regulator would correct for it if everything else were working.

Expert comments on student's suggestion that DCS could also produce these symptoms.

As you have seen I don't suspect the DCS and CL. My strategy now is to use the VC and CC in tests to isolate the fault. I can find out more about the CCS-DA region this way. If there is a fault in that region, neither the VC nor the CC will have any effect.

Strategy is to observe the instrument's behavior under various manipulations of front-panel controls.

Here is how the instrument is set up...

SETTINGS:

CC	1.0
CR	HIGH
LOAD	1000
VC	1.0
VR	HIGH

Does the THE VOLTAGE CONTROL reduce the OUTPUT VOLTAGE ?

DICK: YES

EXPERT:
That's nice! Since the VC is able to change the output voltage, we must conclude that the voltage limiter is responding correctly by drawing enough current away from the base of the Darlington circuit to reduce the voltage at the latter's output. This means that the Darlington is functioning, too, and that the CCS must be putting out a constant current. Briefly, the voltage regulating action of the supply seems to be unimpaired, and so, I think that perhaps the output voltage of the Vref is not OK. Your fault is in the Vref.

As it happens, the first such observation is sufficient to locate the fault. The Expert explains why.

Am I right?
DICK: YES
EXPERT:
I'm glad...

Would you like to isolate the actual component fault?

DICK: YES

Entering SOPHIE lab...

OK, here is a review of the measurements made so far:

CC=1.0, CR=HIGH, LOAD=1000, VC=1.0, VR=HIGH, THE OUTPUT VOLTAGE IS 34.4 VOLTS.

CC=1.0, CR=HIGH, LOAD=1000, VC=0.0, VR=HIGH, THE OUTPUT VOLTAGE IS 2.83 VOLTS.

CC=1.0, CR=HIGH, LOAD=1000, VC=1.0, VR=HIGH, THE OUTPUT VOLTAGE IS 34.4 VOLTS.

```
Go ahead and locate the faulty component:

>>WHAT IS THE VOLTAGE ACROSS C1?
THE VOLTAGE ACROSS C1 IS 71.3 VOLTS.
```

Student takes a "signal tracing" approach to finding the fault within the faulted block.

```
>>AND ACROSS D4?
THE VOLTAGE ACROSS D4 IS 56.0 VOLTS.

>>AND D5
THE VOLTAGE ACROSS D5 IS 41.4 VOLTS.

>>REPLACE D5
I AM GOING TO ASK YOU SOME QUESTIONS ABOUT HOW  D5
IS FAULTED.
```

SOPHIE requests more detail about how the student thinks the component is faulted.

```
IF AT  ANY  TIME  YOU  WOULD  LIKE  TO  MAKE  MORE
MEASUREMENTS, SIMPLY TYPE CONTROL-E.
IS D5 OPEN OR SHORTED OR DOES IT  HAVE  THE  WRONG
BREAK-DOWN VOLTAGE?
> OPEN
D5 REPLACED.

Now you should take measurements to see  if  there
is anything else wrong with the circuit.
ACCUMULATED COST = 16

>>WHAT IS THE OUTPUT VOLTAGE?
THE OUTPUT VOLTAGE IS 30.1 VOLTS.
```

Student verifies that instrument now works.

```
>>STOP
```

Chapter 5

QUESTIONNAIRE AND TRANSCRIPT RESULTS

The purpose of this chapter is to provide a comprehensive summary of how students reacted to and benefited from the SOPHIE environment. The students' experiences were gathered during self-contained mini-courses which involved students' studying textual material, interacting with the Expert Debugger program, performing laboratory exercises and engaging in both team and solo troubleshooting, as described in Chapter 1.

SOPHIE's learning environment incorporates a variety of instructional activities and teaching systems, many of which are novel to the teaching of electronics. We could have investigated their total impact to determine, for example, if the mini-course supported by the SOPHIE system was more effective than a segment of some existing training program. However, this was not our purpose. Such comparative investigations can only be meaningfully undertaken after one has understood how to exploit the novel capabilities of SOPHIE-like environments and how to tune these capabilities to the interests and abilities of the student. The intent of these experiments was to determine the viability of each activity and to assess its effectiveness relative to the others. As such, we focussed most of our attention on qualitatively assessing student reactions to individual components of the learning matrix. We also paid close attention to the kinds of questions students had while engaging in each activity and to the difficulties they had in understanding particular aspects of the device under study. Being able to build a taxonomy of their questions and misconceptions is of crucial importance for tuning intelligent, generative systems. Unlike frame-oriented systems which have the answers to a small set of questions explicitly stored, a generative system must be able to answer a wide variety of questions which depend on the particular context. In large part, this capability can be achieved by knowledge of what types of problems and misconceptions are apt to arise. Communication is drastically facilitated when the listener (SOPHIE) has a good model of what the speaker (student) is thinking.

QUESTIONNAIRE

In our initial set of experiments, three groups of students participated. Two of these groups (eight people) took the mini-course over four successive Saturdays, the other group did it on four consecutive days. At the end of the 12 hour training sessions, each participant filled out a questionnaire probing his reactions to each of these activities. Finally, we conducted an in-depth interview with each group.

The first part of this chapter discusses the responses taken from these questionnaires for each of the activities.* The single questionnaire which was used for each of these activities is presented in Figure 1.

Individual Troubleshooting

Individual troubleshooting is perhaps the most conventional use of the SOPHIE system. Typically, the instructor inserts a fault in SOPHIE's simulated IP-28 and then the student isolates it by making measurements.** When the student locates the component that he thinks is faulted, he requests that it be replaced. At that point, SOPHIE will query him about how the component is faulted. If he is right, the component is replaced and he is asked to verify that the instrument is now fixed.*** If he is wrong, SOPHIE will automatically critique his "guess" by pointing out to him which of his measurements support that "guess" and which contradict it.

Individual troubleshooting activity occurred throughout the mini-course, but it was used most heavily in conjunction with the Expert Debugger and at the end of the course. During this latter activity, we turned on the costing function: each measurement was assigned a cost according to how difficult it is to make in a real instrument.

Figure 2 graphically summarizes the results of the first six items on the questionnaire (Figure 1). Figure 3 presents all of the collected responses to the last item.

---

*Although we made some minor changes and refinements to this mini-course between successive groups, we shall lump together their responses.

**The student can also insert the fault himself by knowing the fault number. In addition, he can have as much practice as he wishes by asking SOPHIE to insert random faults of some specified degree of difficulty (easy, hard, extremely hard).

***If he has replaced a secondary (propagated) fault, the component will be re-blown when he tests to see if the instrument is working.

Basic Questionnaire Format

(1) How enjoyable did you find using this system?

1	2	3	4	5
very boring	boring	interesting	exciting	very exciting

(2) Was it useful in teaching you how to be a better troubleshooter?

1	2	3	4	5
useless				very useful

(3) Was it useful in teaching you deductive or logical thinking about circuits?

1	2	3	4	5
useless				very useful

(4) Was it useful in helping you understand how the IP-28 power supply works?

1	2	3	4	5
useless				very useful

(5) Was it valuable in teaching you basic electronics knowledge that you can now apply to other circuits?

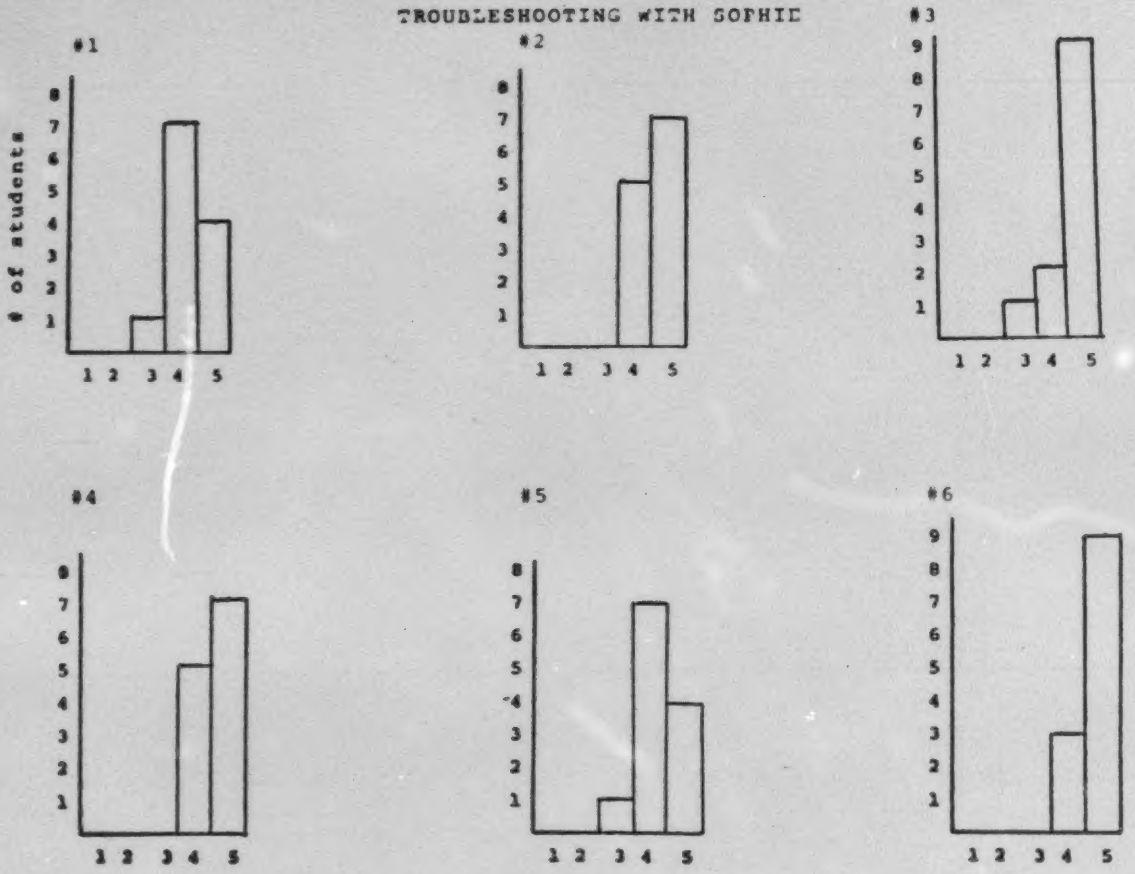
1	2	3	4	5
useless				very valuable

(6) How would you rate using this as an educational experience?

1	2	3	4	5
very low	low	average	high	very high

(7) What is your overall impression of this activity?

FIGURE 1



(1) How enjoyable did you find using this system?
(very boring (1) to very exciting (5))

(2) Was it useful in teaching you how to be a better troubleshooter?
(useless (1) to very useful (5))

(3) Was it useful in helping you deductive or logical thinking about circuits?
(useless (1) to very useful (5))

(4) Was it useful in helping you understand how the IP-28 power supply works?
(useless (1) to very useful (5))

(5) Was it valuable in teaching you basic electronics knowledge that you can now apply to other circuits?
(useless (1) to very valuable (5))

(6) How would you rate using this as an educational experience?
(very low (1) to very high (5))

FIGURE 2

QUESTION 7

What is your overall impression of the TROUBLESHOOTING WITH SOPHIE activity?

1. The main thing I learned is to discriminate between a faulted component and a component that can´t function properly because of a fault somewhere else. I think this is difficult because of the various interactions between the components. However, to be able to do this well is very desirable.

2. Excellent way of learning logical thinking which enables you to see your mistakes. It was a good test on a person´s background knowledge.

3. Very useful and something that should be mixed in with the Expert-Debugger as a preliminary exercise. (i.e. (1) work with expert, (2) work with SOPHIE, (3) work with expert, (4) work with SOPHIE.) I think that a pattern similar to this would help the student retain more of what he learned with the expert.

4. Excellent - much more valuable than time consuming lab work.

5. I think this was the best of SOPHIE´s menu choices. She guided you but at the same time, let you alone. I think I learned the most from this.

6. Very good. It taught you to think in the line of action/reaction as SOPHIE would tell you where you went wrong if you tried to replace the wrong component.

7. At certain times SOPHIE made me believe that I didn´t know that much in electronics, but finally I did enjoy it.

8. I thought it was very useful and practical. This was the best approach to learning the equipment. It had a high interest coefficient and its competitive nature (when playing with other groups in solving the same problem) made it an exciting way to learn.

9. I found this to be very valuable in learning troubleshooting, in what you can see on your own, however if SOPHIE could tell you reasons or hints as to if you are doing anything wrong in you reasoning, it would increase its utility by far.

10. If you had an active power supply to take measurements from and could relate to the computer for help it could be easier troubleshooting, but was very good.

11. This was good. It taught you a lot about how to troubleshoot this circuit as far as how well this will help you with other circuits, I´m not sure how helpful it would be.

FIGURE 3

We were encouraged by the degree to which students accepted this activity, since it was the least directed of all the activities. From the various oral comments the students made, the feature they found most beneficial was being able to make any measurement quickly. Although they realized that "real world troubleshooting" is different, this rapid interaction encouraged them to explore. Students often commented that they invariably wasted a lot of time in their school labs because the right equipment was either not handy or broken.

On the negative side, we felt SOPHIE's ability to critique a student's troubleshooting path and to answer his more general "why" questions was noticeably deficient. Although SOPHIE does perform hypothesis evaluation, this form of critique was insufficient. First, it doesn't satisfactorily explain why a hypothesis is incorrect; it can only show which measurements are inconsistent with the hypothesis. Unless a student can translate this information into more causal terms, he has a difficult time extracting and remembering the essence of the example. Second, SOPHIE delineates only the logical inconsistency of a hypotheses and does not comment on the strategic reasonableness of the actual sequence of measurements. Finally, a student only receives feedback after he thinks he has located the fault. To remedy these deficiencies we need a tutorial module which has sufficient intelligence to know when and how to help the student while he troubleshoots.

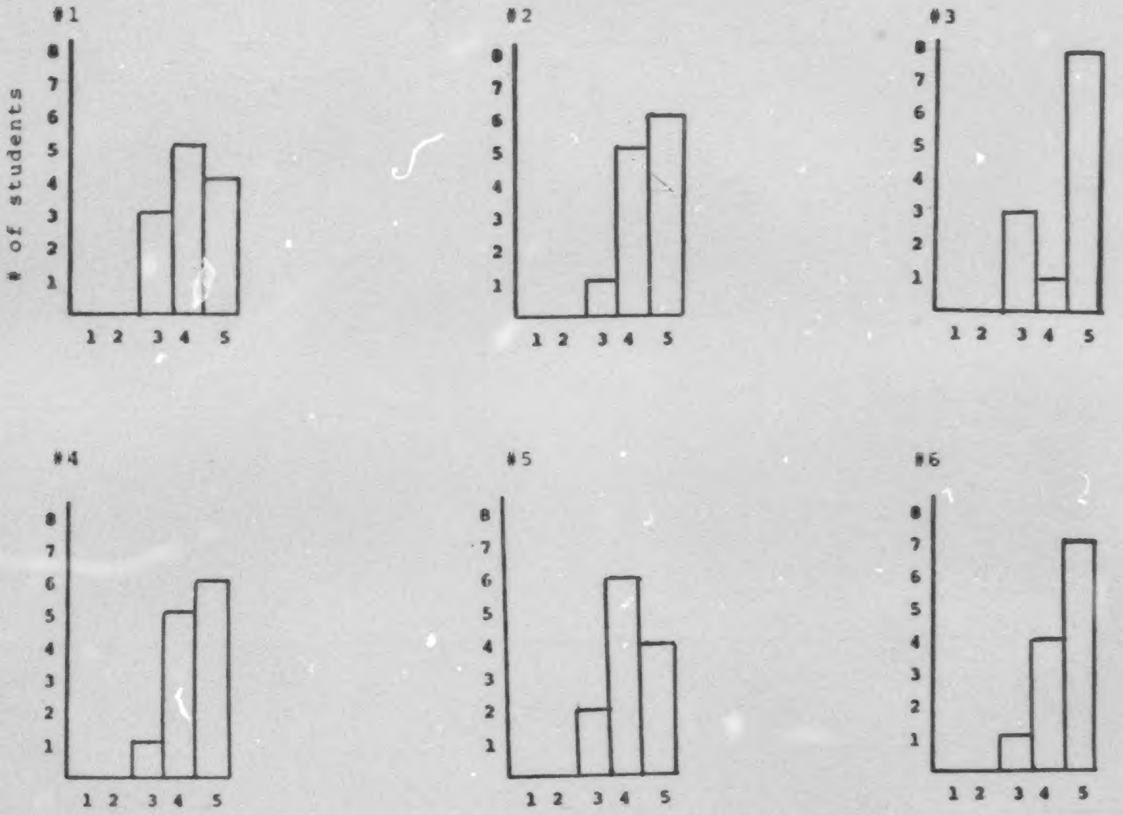
Team Troubleshooting

The team troubleshooting game was described in Chapter 4. Note that although the rules for this game are rather involved, most of the students quickly learned how to play. The game's basic structure was obvious enough that the fine points fell easily into place.

Team troubleshooting took place during the last two sessions. Figures 4 and 5 present the results of the questionnaire for this activity.

Although the game provides a strong motivational factor, we discovered some problems with it. First, the game was much harder than we had expected. Teams were inserting faults whose behavior they simply couldn't predict. Obsessed with giving the other team a really devious fault, they often found that they couldn't even set up the instrument to reflect a symptom under their fault. The result was an excessive waiting time for the opposing (troubleshooting) team.

TEAM TROUBLESHOOTING GAME



(1) How enjoyable did you find using this system?
(very boring (1) to very exciting (5))

(2) Was it useful in teaching you how to be a better troubleshooter?
(useless (1) to very useful (5))

(3) Was it useful in helping you deductive or logical thinking about circuits?
(useless (1) to very useful (5))

(4) Was it useful in helping you understand how the IP-28 power supply works?
(useless (1) to very useful (5))

(5) Was it valuable in teaching you basic electronics knowledge that you can now apply to other circuits?
(useless (1) to very valuable (5))

(6) How would you rate using this as an educational experience?
(very low (1) to very high (5))

FIGURE 4

QUESTION 7

What is your overall opinion of the TEAM TROUBLESHOOTING GAME activity?

1. This made learning troubleshooting much more interesting since you have to insert a difficult fault and at the same time predice the consequences.
2. This system was very good because it allowed you to find a bad component and be under expense pressure at the same time. The idea of teams is very good because we were able to discuss the faults of the circuit and also see the reactions of the fault by watching the other team troubleshooting the circuit. This game also showed us to answer the other team´s questions; this gave us the opportunity to see if we really knew the fault well enough to troubleshoot it ourselves.
3. I found this good for using other people´s ideas in solving a problem when one person may be completely baffled. (Two heads are better than one.) Gives you a chance to work with others by reasoning and then finally agreeing together.
4. The team idea lets you pool information. But it also allows for more "devious" faults to be inserted and discovered than if it was 1 against 1.
5. I found it to be useful in that you and your teammates would have different ideas to be exposed to Sophie and through reasoning with your partner maybe one measurement can be made that would help out you and your partner´s reasoning at the same time.
6. Excellent - The emphasis here was placed on logical thinking about the circuit.
7. Very good educational approach to learning the equipment.
8. This was also good but teams don´t always work well together. It would be better if each team was 1 person.

FIGURE 5

In many ways it seemed that the side that inserted the fault learned more from the game than the side performing the troubleshooting. This might seem counter-intuitive, since the inserting team presumably chose a fault whose ramifications they knew. However, because of the structure of the game, their understanding of the fault was constantly being tested. As a result, the inserting team would often discover shortcomings in their own knowledge. They would discuss such problems between themselves, and often ask us or other class members for help after the game.

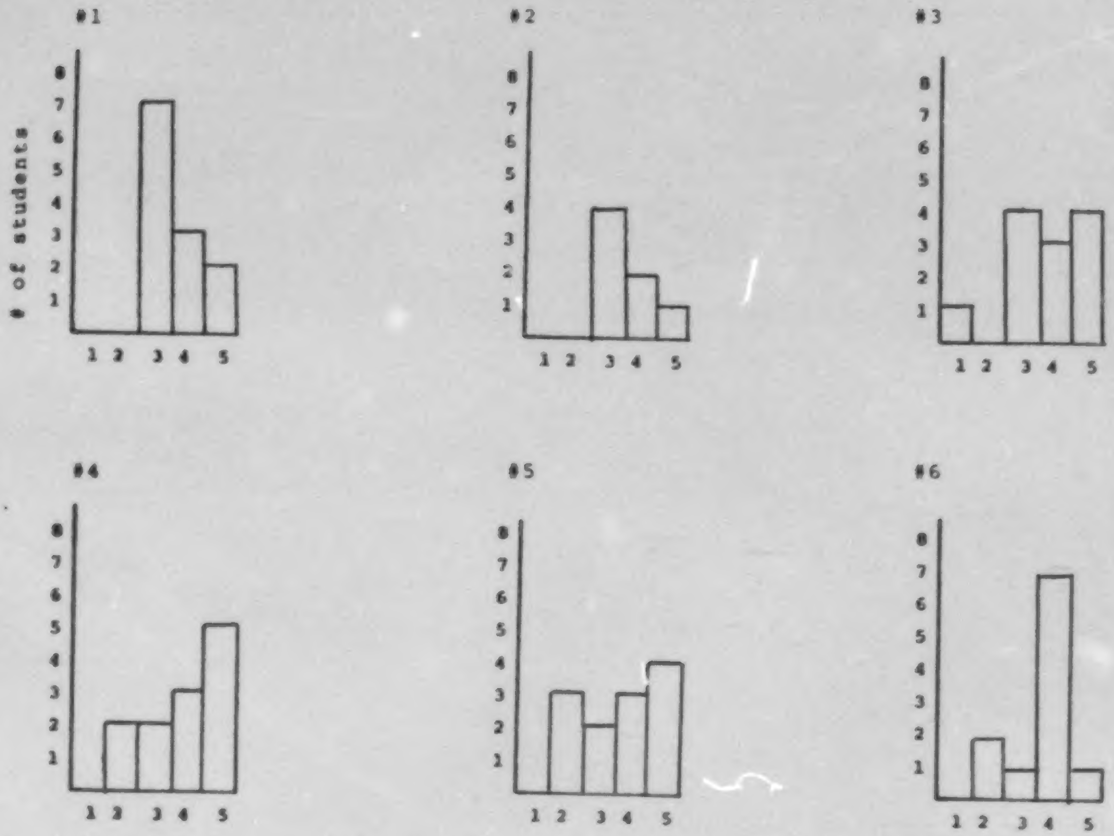
The Expert Debugger

The Expert Debugger was the most directed activity in the environment. Its purpose was two-fold. First it attempted to teach troubleshooting and the workings of the IP-28 by explicit examples coupled with explanations. Second, it provided an opportunity for the students to exercise their causal understanding of concepts such as feedback by continually asking them to predict the consequences of faults.

This was the first major activity following the use of the instruction booklet. It was also the newest subsystem of the environment: some bugs uncovered by the first group had to be fixed before the second group used it. Activity in the second three-hour sessions involved alternating between the Expert Debugger and solo troubleshooting. By going back and forth between directed and undirected troubleshooting, the student would begin to appreciate the subtlety of what Expert Debugger was saying and doing. Also, when the student moved from the Expert to solo troubleshooting, he would sometimes encounter a situation similar to one the Expert had explained and hence would have a chance to test his own understanding of what the Expert said. Figures 6 and 7 contain a summary of the results of the questionnaire pertaining to this activity.

Although these results indicate that the students found this system very useful, we felt from listening to them as they used it that the system could have been much more effective. In particular, it appeared that much of what the Expert "said" was not being absorbed by the students. This could be due to at least two factors. First, the Expert's reasoning is presented in a relatively passive mode. Not only can't the student ask for elaborations on things the Expert says, but the Expert seldom comes back and queries the student about what it has said. Second, the Expert is totally non-adaptive. The explanations it produces do not depend on the competence or history of the student. This means that some students do not understand all of what the Expert is trying to get across and others find its speed and

EXPERT/DEMON BLOCK LEVEL DEBUGGING



(1) How enjoyable did you find using this system?
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(5) Was it valuable in teaching you basic electronics knowledge that you can now apply to other circuits?
(useless (1) to very valuable (5))

(6) How would you rate using this as an educational experience?
(very low (1) to very high (5))

FIGURE 6

QUESTION 7
What is your overall impression of the EXPERT-DEBUGGER BLOCK LEVEL DEBUGGING activity?

1. It was good for helping me to evaluate my train of thought and training. It was constantly testing my understanding without the pressure or formality of a written exam.

2. I thought it was very good because I did learn a lot and the way it was presented was exceptional.

3. My impression of this activity is very good because that's the first time I got the chance to put my background in electronics into practice.

4. Using the expert gave another way of looking at the problem in the circuit.

5. I think all of the above questions express my opinion of this course. I enjoyed it very much and found it most interesting.

6. My overall impression was the Sophie was useful; particularly in the area of troubleshooting and debugging but not so much in teaching basic electronics. For example, we were expected to all ready know basic transistor theory.
   (Note: They certainly were!)

7. Very good for finding generalized faults in a circuit.

8. Having never troubleshooted before this gave me some very helpful and practical experience. However, if the Sophie reasoning (Expert) was slightly slower at first, I could have followed along easier, and therefore learned (or whatever) the expert's reasoning process.

9. It rushed the student and left a lot of questions. If the bugs were out of the system it would be a lot better, also no good on CRT. Explanations run off screen before they are understood.
   (Note: The first group of students helped us debug this subsystem.)

10. The functional block approach is very good. It would be better if a basic overview of the circuit's operation were explained beforehand.

11. I thought that it might have worked well if the system hadn't messed up on when we asked it a question. Also it probably would have been more useful had we understood the IP-28 power supply better.

12. Interesting.

FIGURE 4

logic a bit discouraging.* Nevertheless, as Figure 7 shows, no one got too discouraged. (Figure 7 includes all of the student responses.)

Fault-Propagation

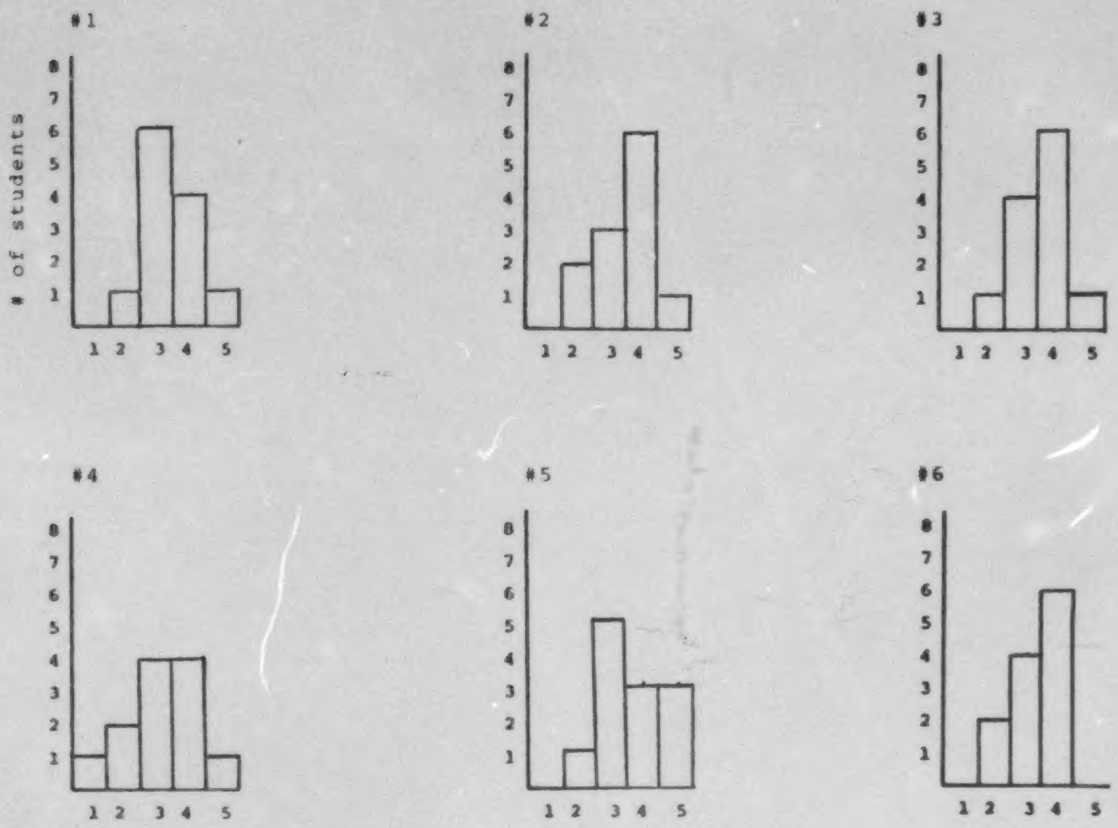
. The final activity for which we constructed a questionnaire concerned "fault propagation." This activity took the form of having the student search for a way of faulting the circuit which would cause a specified component to fail. That is, the student would have to insert a fault (such as shorting some other component) that would cause the specified component to be overloaded. The learning object underlying this activity was to give a student explicit experiences in predicting consequential faults. Before he blindly replaces a burned out component, he should think about possible reasons that the component might have failed.

Figures 8 and 9 present the results of the questionnaire for this activity. As one can see, students' reactions were considerably more mixed than for the other activities. Comments five, eight, nine and ten probably provide the clue to why it was less well liked -- students encountered this activity too early in the mini-course. Since this task requires detailed understanding of the purpose and interaction of the modules in the IP-28, a student with insufficient knowledge would have trouble. For example, he might insert a fault that does nothing or conversely, that blows out many components. Encountering either of these situations could be very educational, but only if the student can make sense of what transpires. The same kind of problem also arises, but less prominently, for local propagations, that is, propagations within a functional module. However, in this case most of our students had the prerequisite theory to understand what was or was not happening when they inserted a fault. In summary, we think this activity has a unique educational role and belongs in the SOPHIE-type environment, but the above-mentioned prerequisites must be met for students to make maximal use of it.

---

*Part of this non-adaptability stems from the sought-after simplicity of this system. More recently we have developed a production rule technique for reconstructing this Expert which will alleviate the above two shortcomings while preserving its modest use of computational resources. This new system is being developed, in part, under a tri-service contract.

FAULT PROPAGATION - BLOWING UP SELECTED COMPONENTS



(1) How enjoyable did you find using this system?
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(2) Was it useful in teaching you how to be a better troubleshooter?
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(3) Was it useful in helping you deductive or logical thinking about circuits?
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(5) Was it valuable in teaching you basic electronics knowledge that you can now apply to other circuits?
(useless (1) to very valuable (5))

(6) How would you rate using this as an educational experience?
(very low (1) to very high (5))

FIGURE 8

QUESTION 7
What is your overall impression of the FAULT PROPAGATION - BLOWING UP SELECTED COMPONENTS activity?

1. Excellent for deductive thinking, trying to see ahead of time that a particular fault will cause a particular blow out.

2. Good in respect that you don't very often get the opportunity to destroy components and see the reaction of the other components.

3. If a component in an existing circuit is blown it might not have been that component that was bad. Something could have caused it to blow. This exercise helped to see what could cause a component to blow.

4. Sometimes its harder to insert a fault for a purpose (blowing up a particular component), than one may think.

5. This activity would have been more helpful toward the end of the sessions. The debugging helped familiarize us with the circuit as well as economizing our measurements, but blowing up selected components when we did (2nd week) was somewhat early in the game to be most useful.

[illegible]. I had thought it to be excellent because we could notice the effects on the circuit more closely when a component is destroyed in the circuit and what its effects would be on the rest of the circuit.

7. Once again, my overall impression of this activity is very pleasant. I do enjoy it.

8. My overall impression was one of frustration. When you don't want something to blow, everything blows and vice versa.

9. This activity was frustrating since our basic knowledge of the circuit was lacking.

10. This is a backwards approach. Too much time is spent guessing what the results would be with the fault installed and if this current was enough to blow the component you were attacking.

FIGURE 9

Overall Impressions

In order to discover the overall impressions that students had using the entire SOPHIE learning environment, we created a separate questionnaire. We asked them how useful the total experience was, how they contrasted it with their normal courses and labs, and what overall suggestions they had on how to improve the course. After they completed this final questionnaire, we also conducted a group interview in which we had a chance to probe more deeply some of their reactions.

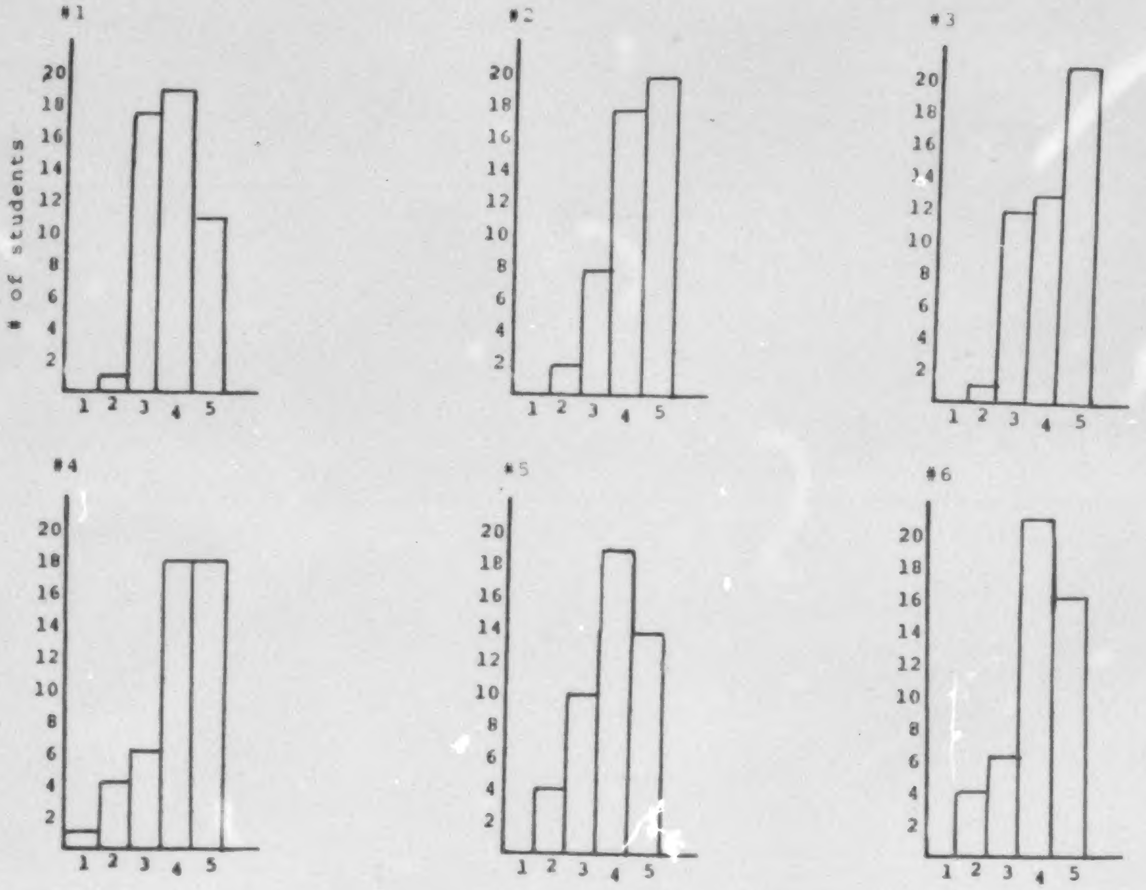
Toward providing an overview of their general reactions to the mini-course, we will present and discuss a summary of all the students' responses to questions, a complete record of all the written comments from the final questionnaire, and and an annotated transcript of one of our group interviews. Although we were at first inclined to extract relevant sections of this transcript, we decided to include the whole, annotated in such a way that readers could skim through it and find comments on issues that might be of particular interest.

Figure 10 presents a summary of the previously mentioned questionnaires which asked the same set of questions of each of the activities. These graphs were obtained by combining responses to each question over all the activities, thus providing some insight into reactions to the total environment. There were two interesting results that emerged from this summary. Although our interest was in teaching generalizable skills, this mini-course involved only one circuit. We were, therefore, skeptical about how far we could get toward teaching general skills. Nonetheless, the responses to question 3 and to questions 4 versus 5 seem impressive.

The response to question 3 indicates that the students believed that they were learning logical skills applicable to more than one circuit. This fact was further reinforced in the group interviews. In fact, someone in the first group (interview) stated that he thought he had learned a general purpose problem solving strategy which pertained to more than just electronics. On further questioning it turned out that what he had learned was the powerful problem solving strategy of top-down decomposition of a problem into more manageable sub-problems. He said he learned this from the way the Expert Debugger viewed the task of troubleshooting.

The responses to questions 4 and 5 give further indication that more general skills were learned. After such concentration on one instrument, we were surprised by

SUMMARY OF ALL ACTIVITIES TOGETHER



1. How enjoyable did you find this system?
   (very boring (1) to very exciting (5))
2. Was it useful in teaching you how to be a better troubleshooter?
   (useless (1) to very useful (5))
3. Was it useful in teaching you deductive or logical thinking about circuits?
   (useless (1) to very useful (5))
4. Was it useful in helping you understand how the IP-28 power supply works?
   (useless (1) to very useful (5))
5. Was it valuable in teaching you basic electronics knowledge that you can now apply to other circuits?
   (useless (1) to very valuable (5))
6. How would you rate this as an educational experience?
   (very low (1) to very high (5))

FIGURE 10

how high students rated the degree of general skills relative to the specific skills of how to work on the IP-28.

We are still very cautious in concluding very much from this data since, of course, the above pertains to what students thought they learned as opposed to what they may have actually learned -- something which is much more difficult to realistically assess.*

The next question explicitly covered the total 12 hour mini-course. The first six questions (see Figure 11) were set up in pairs comparing activities in the SOPHIE environment with corresponding activities in the students' school. Using school activities as a reference point provides a high standard for comparison. Nearly all these students had chosen their school over a much cheaper local state school because of its reputation for small classes and excellent training.

Of particular interest to us was the comparison of responses to questions 3 and 4 which seems to give additional support to our belief that the troubleshooting scenario might be an effective medium to learn a certain kind of qualitative electronic theory.

The last five number-line questions are summarized in Figure 12. Several of these are worth mentioning. Question 7, concerning what proportion of a troubleshooting course should be based on SOPHIE-like environment, generated a surprisingly uniform (and in our opinion, too high) response. We feel that actual laboratory experience is crucial, as we have argued above, although a lot of factual instruction time might be converted over to more of these semi-laboratory situations.

The response to questions 12 and 13 was also noteworthy. The relatively high slope on 12 indicated a favorable reaction to the natural language front end processor, although several students kept expecting it to handle everything once they found out it could handle something.

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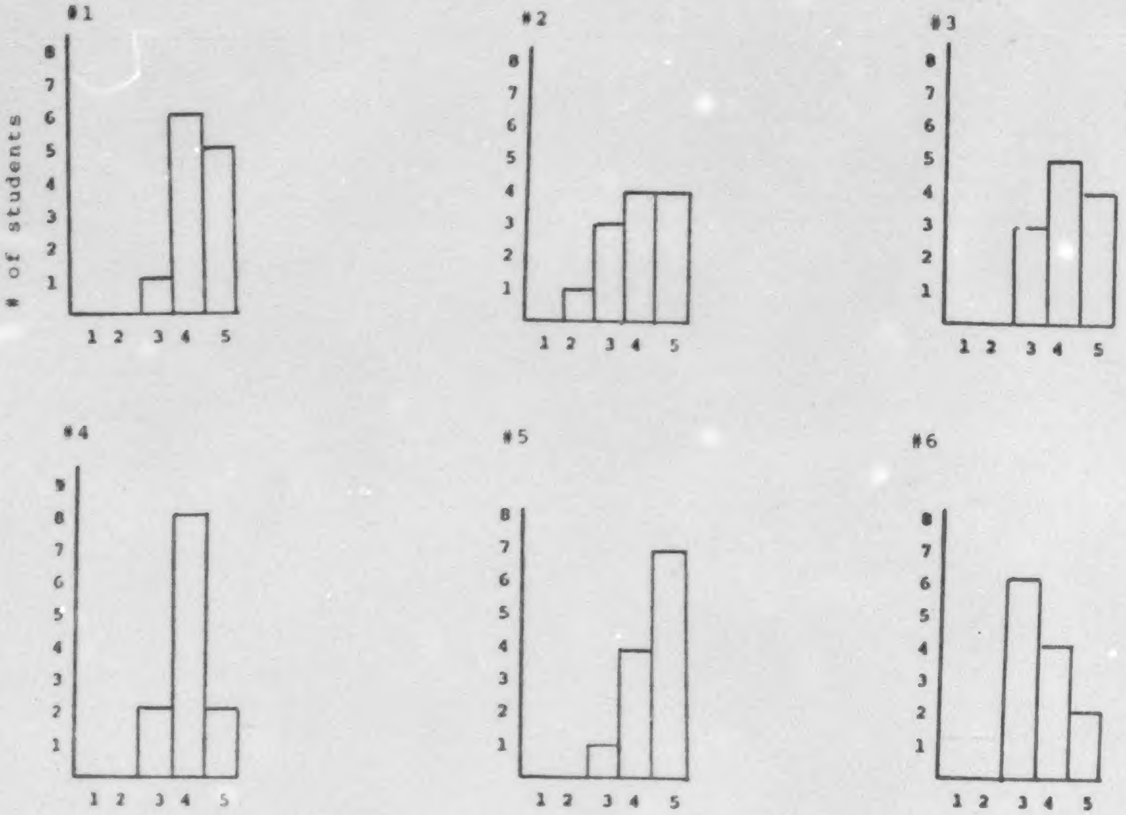
*We make no pretense about the objectivity or quantitative nature of these survey results. We hasten to point out that measuring these more general skills in an unbiased fashion is extremely difficult. In particular, we believe that because this environment stresses learning through personal actions and experiences, the skills they acquire will be remembered for a long period of time and will be more broadly applicable than those learned through more passive or factual modes of instruction. We would hope that any objective tests would develop techniques to measure the longevity as well as the generality of these skills.

OVERALL RESULTS



(1) **How effective were these four sessions as a laboratory experience?**
(useless (1) to very valuable (5))

(2) On the same scale, how do you rate your laboratory courses?
(useless (1) to very valuable (5))

(3) How effective were these four sessions as an electronic theory learning experience? In particular did you find that theoretical ideas became clearer to you by using this system?
(learned no theory (1) to a great many ideas became clearer (5))

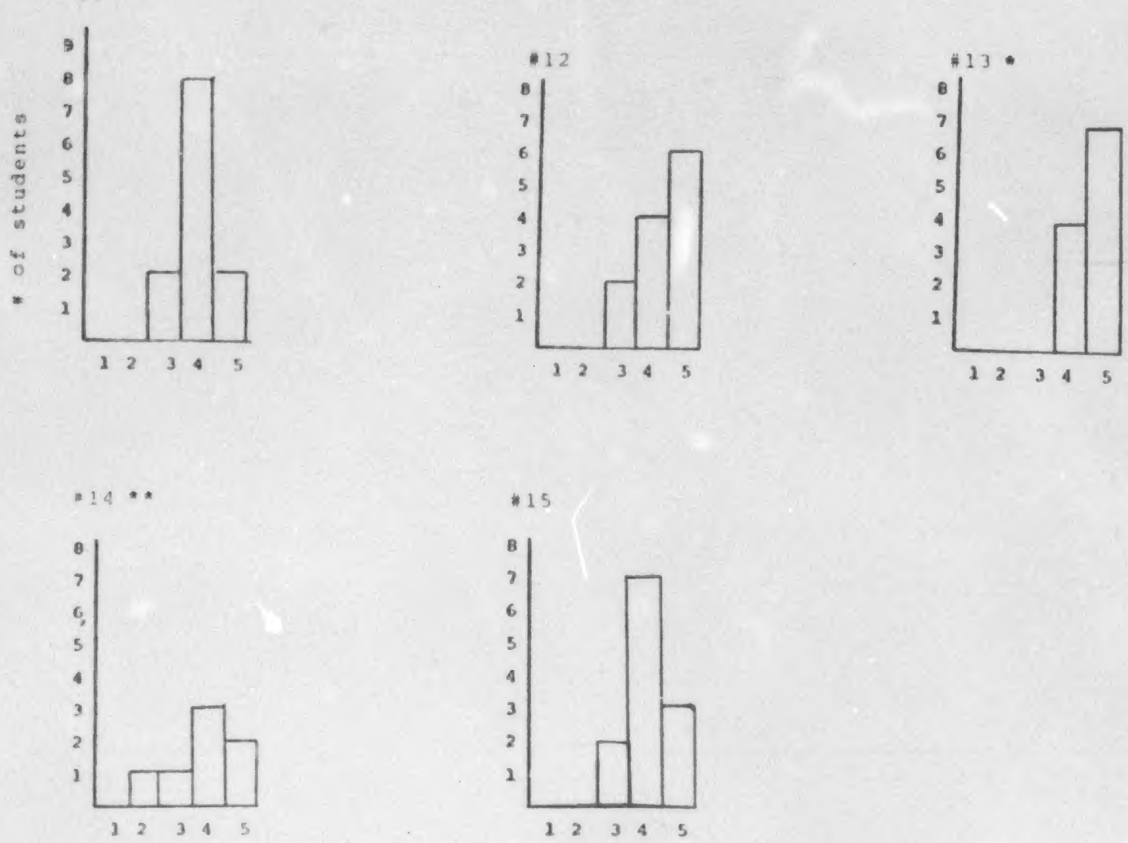
(4) On the same scale, how would you rate the average 12 hours of theory courses that you have had in school?
(learned no theory (1) to a great many ideas became clearer (5))

(5) Was the experience enjoyable and engaging?
(boring (1) to very exciting (5))

(6) On the same scale, how enjoyable and engaging are your classes in school?
(boring (1) to very exciting (5))

FIGURE 11

OVERALL RESULTS (CONT.)



(7) In a complete troubleshooting course sequence, what proportion of our type of computer-based experience would be best? (all regular labs (1) to all computer labs (5))

(12) How "friendly" did you find our system? (very hostile & intimidating (1) to very friendly & nonthreatening (5))

(13) How clear did you find the instruction booklet? (very hard to understand (1) to very clearly written (5))

(14) Did you find the questions in the instruction booklet helped you concentrate on the factual material in the booklet? (useless and bothersome (1) to very useful (5))

(15) Did you find the various activities with the computer system a major help in furthering your understanding of the factual material in the booklet? (no help at all (1) to extremely helpful (5))

*1 student did not answer
**5 answers not applicable

FIGURE 12

Similarly, their responses to question 13 indicate that our design and implementation of the instruction booklet was successful. This is of interest for two reasons: We think the technique we were using to explain certain concepts (as discussed in Chapter 2) is of general use, and we wanted to be sure we were not just constructing a "straw man" against which some people might want to compare the computer-based environment. We had no intention of making any comparisons at all, but instead simply wanted to exploit the best features of programmed instruction.

The last part of this questionnaire consisted of several of the questions which required written responses. Figures 13, 14, and 15 present all the collected responses to these questions. The responses to the question concerning "how your view of troubleshooting has changed as a result of the mini-course" indicates some explicit skills these students learned. The responses to the question concerning which activity they liked the best (and why) provides some insight into some of the sociological factors underlying this environment. (See Figure 14.) The last figure illustrates some of the weakness that still exists in our system.

QUESTION 8

How has your view of troubleshooting changed as a result of this experiment (i.e. the whole 12 hour instructional sequence)?

1. A more logical approach and an understanding of interactions. In school lab I had a tendency to replace every component in sight until the problem disappeared. Classroom schooling time is invaluable and most important. But SOPHIE allows you to use the theory and see how it works - put the ideas into use.

2. The computer has one major advantage over practical troubleshooting, that is, that SOPHIE eliminates any problems of measuring components values that might occur under normal conditions. This lets one concentrate on actual troubleshooting and solving the problems rather than worrying about having the probe on the right spot. Confidence and uncomplicated experience (measuring) can build a strong troubleshooting foundation.

3. This course has helped me understand the action/reaction part of troubleshooting better because I got a chance to see things in a circuit I was never able to see before.

4. My troubleshooting theory has been better defined.

5. I think it has broadened my view of troubleshooting and feel that this experiment has been extremely useful and find troubleshooting not as difficult by knowing more of what to look for.

6. I didn´t have much troubleshooting experience before, so I was pretty much ready for anything. SOPHIE demonstrated troubleshooting in pretty much the way I would have imagined it (except for using the computer of course).

7. Not as hard as I thought.

8. Not much, I´ve done a lot of it and my methods worked well with your system.

9. I have realized that there is much more to troubleshooting than previously expected, i.e. much more logic is needed.

10. It has changed my view in that the problem always isn´t what you first expect but that some other part of the circuit could be resulting from something else in the circuit.

11. That the first time I had one.

FIGURE 13

QUESTION 9

Which of the various activities did you enjoy most and why?

1. Troubleshooting since you relied on yourself to solve the problem.
2. Team troubleshooting - because of the game aspect (competition) and because I had help - with 2 people you can test out. You reason with each other before making a move.
3. TEam troubleshooting game - It gave us a chance to stump someone else instead of the machine stumping us. It also gave us a better understanding of the circuit because we had to feed the machine with the correct answers.
4. Troubleshooting with Sophie - gets you to think logically, not haphazardly and at the same time lets you see your errors.
5. Expert-Debugger was the most interesting because if you made a wrong guess it would use detective reasoning to find out why your answer was incorrect and find the fault you selected.
6. Troubleshooting with Sophie (in which she corrects you when you are wrong) because I thought it was the most useful to me, education-wise.
7. Troubleshooting with Sophie because I could follow my own logic, and learn at my own pace.
8. Troubleshooting with Sophie because I learned much better from it.
9. Troubleshooting with Sophie because I thought it was very useful and practical. This was the best approach to learning the equipment. It had a high interest coefficient and its competitive nature (when playing with other groups in solving the same problem) made it an exciting way to learn.
10. Team troubleshooting because more ideas were being brought to our attention about the circuit.
11. Troubleshooting with Sophie was more enjoyable since it lacked the pressure of competition.
12. Troubleshooting with Sophie - personal challenge with your errors pointed out and explained.

FIGURE 14

QUESTION 10

What are your overall feelings about this system and what suggestions do you have for making our system a better teaching device?

1. I feel that the system was very good. The only difficulty may be with the expert; he may move a little too fast for some people. I found it a little too hard to keep up. While I was reading his thoughts he was starting new measurements but his logic was good.

2. Good. It's very helpful to be able to answer any question about the circuit by setting up the circuit immediately and using it. What if this happens? Well I can try it and see. Without the real time problems of physically setting up the circuit and arranging or replacing components. I like the short time interval between question and the answer.

3. Less time with Expert-Debugger and more time troubleshooting.

4. I enjoyed the whole experience very much and I think a course (at say Wentworth) would be great (based on this system). Its format might be the IP-25 for about a month and something more complicated thereafter (still with Sophie). Of course, that would mean a lot more work for you guys because you'd have to come up with a new additional program; but you enjoy your work!

5. In a couple of places Sophie made me unsure of answers that I had given because Sophie told me my answer was wrong then gave me the answer I gave to the computer.

6. Good.

7. Increase its vocabulary. Not bad at all.

8. This system has been deeply useful to me. I don't have any suggestions.

9. Very good.

10. Excellent, however some parts of the system need cleaning up.

11. Excellent. More time on functional blocks.

12. I think it's basically a good idea, but lots of room for improvement. The language needs improvement. If too much time is spent on the terminal it gets boring. I don't know how to help this but it would be a problem.

FIGURE 15

GROUP B FINAL DISCUSSION

EXPERIMENTER: Did you find that you had learned some factual knowledge about how zeners worked or how to [inaudible] and this helped you understand it better. Or somehow make more concrete this factual knowledge.

STUDENT: Practical knowledge more so. like a zener breaking down early is something you wouldn't necessarily think of if you were just studying circuit theory, but when you're troubleshooting. you know, if you just had the circuit theory background to go on, when you were troubleshooting you could look right over that and not ever think that it might break down early. There's a lot of practical knowledge that I did get out of this that I didn't get out of school itself. I may have picked it up after several months of troubleshooting on my own, but it was an easy way to troubleshoot without having to worry about taking the thing apart and inserting the probe at the right spot. If you can get rid of all those hassles it was excellent. And that's exactly what it did, it gave you an ideal atmosphere for troubleshooting. Just like, I'd like to know the current through there and it tells you the current through there. I'd like to know the voltage here. it tells you the voltage there. When you troubleshoot you can think these, but you can't always do them because they like to jam all the components together, and you might short out something just trying to stick a probe in it.

Some practical electronics facts do not come up in theory courses - such as how components fail.

Computer-based lab provides concentrated experience.

E: Do you think it helped you remember theory information better?

S: Yes, it helped me recall some. I think if before the first Saturday I came here, if you asked me what the V of a transistor was I don't think I could have told you. It's around .6, but I wouldn't have thought of it. It would have come to me after working with the stuff, it brings a lot back, yea, I think it does.

Theory information becomes clearer.

E: Okay, so the relevance of that sort of information becomes clearer.

S: Yes, considerably. Like in the laboratory, if we have any problems, we just turn around and look in our book, but not using any books here, just using the schematic sort of requires you to use your memory that you just never have used. It's there but you just haven't bothered to look, or use your own memory because we've been looking in and out of notes and books or whatever.

E: So nobody ever told you that the V of a transistor was something that you really needed to know to debug things.

S: We never learned from a debugging point of view. We just learned from a designing point of view. So this was a new experience, different experience. It was very helpful too.

Theory courses may not point out what is most useful for troubleshooting.

E: What sort of things did you learn about debugging? Where were you before? Where are you now?

S: I was nowhere before. I didn't know anything about debugging before. Now I have an idea of where to start, like I suppose I could have figured that much out beforehand. You're going to start with measuring the output voltage or whatever. If it's a TV you're going to find out if the picture comes in, or the simplest first measurement. But then where to go to, what one measurement tells you, why it eliminates this or why it leaves that still suspect. I knew nothing about troubleshooting before.

Students developed a more systematic approach to debugging.

S: You have to have a certain amount of working knowledge in the circuits but I think there was a lot of practical experience in it that you just couldn't have got unless you went out and did it yourself and you would have had a lot of hassles trying to do it on your own. It would have taken you longer to get the same amount of experience.

S: Well, it would be easier to learn on a computer than having an engineer tell you. We were actually working with it ourselves.

Lab experience is essential to learning troubleshooting.

E: That seemed to make a big difference to you, actually working with it yourself.

S: Yes, a lot of difference.

E: So you found the booklet was fairly clear for you right, but somehow you were still just reading it.

S: Yes, as reference material.

E: Yes, but when you actually came to trying to use the stuff, it became much clearer what everything was about.

S: I think the combination of working with the expert and then working on your own helped you to start a thinking process necessary to debug it in an economical manner. When I first started out I really didn't know where to start because I wasn't that much aware of how the circuits interacted. After watching the expert do some of it and getting to follow his train of thought, I would pick up well, he went from here and then just work backwards to this point just checking in and out and in and out and then sort of went into detail when he found a general area that he thought was wrong. Whereas otherwise I might check in detail something all the way completely through and find out there's nothing really wrong with it at all. This is something you pick up: experience. When you're doing it on the computer it's a lot faster than if you try to do it on your own. I think if I was actually debugging the circuit -- the IP-28 for the first time, and went into great detail on it, I might have spent 4 or 5 hours just going through different components. Now I could probably do it in a half hour, maybe, if it was a serious problem.

Combination of Expert and SOPHIE lab develops a sense of economy and method.

Student thinks he could find a hard fault in the IP-28 eight or ten times faster now than when he started.

E: How do you feel about attacking a circuit that you're not familiar with now? Do you think this has been helpful in developing a general strategy that will make that go better?

What about debugging new circuits?

S: Oh, yes

S: Yes, I think so. I think the first thing I'd do if I was going to attack something completely different is try to break it into blocks like this one is. It has Darlington Amplifier, current source and all that. I'd try to do something like that with it rather than looking at one big schematic with 8,000 components. That would be the first thing I'd try to do.

Strategy learned applies to unfamiliar equipment.

S: Kind of like trying to drive around Boston when you don't know where you're going.

E: What about you? How did you feel about learning more general stuff to be able to approach other circuits besides just the IP-28?

S: I agree with John, it gives us a little bit better outlook on what to look for.

E: I'm kind of curious: something came up in past groups we never thought of. Some kids mentioned the fact that they thought that they were actually learning some logical thinking skills, apart from the electronics, just a kind of more precise common sense reasoning, things like this. How do you guys respond to that?

Does working with SOPHIE help to develop logical thinking?

S: I'd say some logical thinking process. I think that comes with just working on your own [SOPHIE lab] and working with the debugger, you were actually thinking in a logical manner. You know that because you have zero output and the current amplifier is working fine then therefore you know that the current amplifier is okay. It just sort of goes unsaid to something you don't even think about being logical, it's just a natural step.

Perhaps...

more along his [expert's] lines, which is the most logical thinking because it went directly to the problem.

Expert sets good example of logical thinking.

E: If we'd been able to spend more time on one of these things like the expert or troubleshooting by yourself or the hypothesis evaluator, etc., how would you suggest we allocate our time in the future? Do you think we should spend more time on one thing we did not stress this time?

Which SOPHIE activity would you have liked to spend more time with?

S: The one I like the most is the one where SOPHIE would just put in a fault, and you would try to detect what the fault was and if you made a mistake, I guess it was the demon that would come in. And tell you, 'no that's not logical'. I don't remember which menu choice.

The Expert.

S: That was 'Interact with the Expert', wasn't it?

S: That's the one I liked the most.

Working with the expert and then working with a hypothesis series seemed to be... if equally spaced them out then it would be better.

Alternating between Expert and SOPHIE lab.

E: I guess we didn't tell you guys anything about the hypothesis evaluator until today. How did you find that?

Did you like the hypothesis evaluator?

S: I thought it was good because it saved points. [Everyone laughs.] I thought it was kind of a crutch too because it's like if you were in lab and every time you asked a question you turned around and asked the teacher, well could this be wrong, could that be wrong? He could say 'yes', and give you an explanation for this, 'yes', give you an explanation for that. Maybe you should limit the amount of questions you could ask about a certain component. I think if you use that a lot in the beginning, you might tend to rely on it more than your own.

Perhaps it gave too much away...

E: Except that you see this a teaching situation. We could imagine some realistic situations where you talked to other people.

B ..Well I could see that but maybe you should put in a handicap. Start out letting the person ask it any amount of times after say three or four sessions only every other time or something. Some kind of a handicap, because that way the person tends to use his own head. If the person finds out that he's using more and more time, using more of a cost...

E: To turn it around you think that by doing a hypothesis evaluation you get a lot of information.

Hypothesis evaluator provides a lot of relevant information.

E: You get a lot of information, yes, but I would have rather gotten that out of my head.

Students are reluctant,

S: But, that seems a little bit strange because you've got a lot of information because the idea you had in your head had certain problems with it.

S: Okay, but if I ever wanted to ask the same question again, I could just go back and ask the same question, whereas I should have remembered it from the first time I asked it.

and misunderstand the purpose - it's not just a review.

S: Or remembered it enough so you wouldn't have to ask it again.

E: Do you think you learned a lot from looking carefully at what the hypothesis evaluator was telling you?

Did the hypothesis evaluator teach anything?

S: Yea, I suppose. But I did find myself going back and checking over what I had asked before.

Yes, but...

E: What about you?

S: I didn't find myself asking the same questions too many times, but I found myself asking a lot of stupid questions. I even knew they were stupid when I was asking them but I was just frustrated and I knew it wasn't going to cost me any points so I asked them anyway. When it tells you that it will come back and say it does not agree with this fault and it will give you some reasons. Well, sometimes you can pick up a choice little sentence out of those reasons that will lead you to what it really is, so I was just asking anything and everything without getting charged points because I had no idea what was wrong. I just couldn't find it, that was on the 112 fault.

Something to do when stuck.

E: And you?

S: Pretty much the same.

E: So you don't have anything in particular you think we should stress but maybe we should spend more time switching back and forth between the expert and then letting you debug the circuit yourself, with the hypothesis evaluator active.

S: Blowing up the circuits I thought or causing them to blow up came a little early in the game as far as I was concerned because I figured that the reason why you wanted us to do that was so that we could follow back and see how doing something to one component would go back and cause a fault here, cause a fault there and follow it along the line. I didn't have that much of a working knowledge of the circuit when we were doing that and so I didn't get as much out of it. Maybe if we'd waited a week or so later, I would have been able to follow it a lot easier, like today. The idea is that you predict if you want a certain thing to blow up you predict by doing, you know, you think that this is going to do it because of that, but if you don't know how it works you can't really do it.

Liked exercise in which student tried to cause specific propagated faults.

Would have been better later in course.

E: And doing it early didn't really help you understand how the circuit worked.

S: No, just like, well I'll try shorting that out and see what it does.

S: Something's got to give!

S: Yea, right, you know it's going to do something you just don't know exactly what.

S: If you get the right component, you're lucky.

E: Specifically, was it useful for you to go from the functional stuff into debugging and then back into the functional stuff. Remember you did the stuff with the expert and then you did some debugging then we put you back on the expert.

S: Yea.

E: What did you get out of that, that you wouldn't have gotten if we hadn't gone back.

Value of alternating between Expert and SOPHIE Lab:

S: I was able to stop and think of what the guy was actually talking about cause if you listen to the expert constantly, you might tend to just block out what he was saying, because the computer has a certain amount of repetition in its statements and you tend to just skip over it and you might skip over a valid point in between that and another statement.

Relevance of what the Expert says becomes clearer.

E: Were you more prepared to accept and listen to what the expert is saying because you've experienced some of the troubles yourself in troubleshooting it?

S: Right.

E: You guys feel that way too?

S: Yes

S: I thought you learned a lot more when you came back to the Expert: you understand why he was doing it. The first time we went through with the expert he was just amazing he just did everything so flawlessly. I now suspect this and that's out because I did this. If he had the total cost on it, he probably could come up with a 5 on the most complicated error in the thing. After we went on it and we were trying to debug something ourselves and you try to think of what he did, you know, and you aren't necessarily following the proper logic you're just doing what he did. Just blindly following him. After we came back the second time, I think I got a lot more out of it.

Expert seems a bit pat at first, but experience debugging shows that it's harder than it seemed.

S: We had a little more knowledge on the working circuit.

E: Do you think if we'd actually had you go back to read the lesson text maybe the second or third day in the program that it would have helped you too?

S: We had a chance to skim over it again the second week.

S: But I don't know about anyone else, but as far as I was concerned with that circuit and booklet, I tend to read things and not always get everything out of what it's saying. So, if someone had sat down after we read over it, alright, and somebody said this is this and this this and this is this then they interact in this way, then I might have followed it a lot faster and quicker than just reading it myself. Cause it was completely a new circuit to me. I had a general idea of how it worked but I didn't have a total ideal of all the interactions that went on.

S: I thought the booklet was pretty helpful but being in an electronics school, cause you could help more in understanding a circuit. For somebody that was just starting out it would be different material and you would learn a lot more out of it.

E: Anybody that's been through the military already?

S: My father's in the military.

E: But I mean none of you have been through the military training

S: Not through electronics training, no.

E: Okay. When we first announced this experiment, I guess some kid read the announcement in your classes, you probably came because you heard we were going to pay you some money. Were you surprised by what you got out of it? Did it turn out to be more enjoyable than you expected or worse than you expected or...

S: No, it did turn out a lot different.

S: I didn't know what it was going to be and I thought maybe you wanted us to do some work, and I mean actual work. I mean that's usually what you're paid for, is doing some work. Getting in here, it was kind of strange that we were just sitting here talking about these computers sort of.

The course was fun.

S: Yea it was fun.

S: It was fun

E: You found it as much fun as lab course?

S: Well a lot more than a lot of them.

S: When you take, like in our lab courses, we can get hung up on circuit construction, and someone might have stuck a capacitor in backwards and it's not working. You can do all sorts of tests that something's wrong and then you find out you scope is uncalibrated or something like that.

Regular labs can be very inefficient.

S: Plus making a lot of bad components, they buy a large quantity and they get them cheap from Teledyne and stuff like that, and they don't always work right. They assume that it always works right but it doesn't always. You might spend 4 hours in a lab just finding out that you had something stuck in backwards or something. Or that the component was bad and that tends to frustrate you. Whereas in here you don't have to worry about that because it sort of goes unsaid that everything is going to work okay, as long as the program works everything else will work okay.

SOPHIE environment is less frustrating than regular lab.

E: So you think that this was a more compact learning experience, when you compare this with...

S: Streamlined would be a better way...

A streamlined approach.

E: So, relative to three or four lab experiences you found out you might have learned a lot more here?

S: [All respond yes]

S: Compared to three or four lab experiences and one for lab, yea I think so.

S: I think if they gave us the same power supply in school and asked us to troubleshoot it we wouldn't have got half as much out of it nor would we have been able to make heads or tails of it very quickly.

S: We'd probably spent the first hour and a half of the thing just trying to take the case off of it or something or they'd find the nuts would be rusted up to no one could find a screw driver.

little things.

S: Monotonous things.

E: Did you talk to people in the other sessions?

...

E: How would you see this sort of thing fitting into a curriculum?

SOPHIE as part of a curriculum?

S: I think it would be good. It would be a nice thing to be able to set up at school, so that say, have it once a week or something if you go in or maybe even at your leisure. Or, you could have it for credit. It would be a nice thing to set up on your own so you could practice debugging but it also would be good if you could set up an actual program where it went progressively. Increasing and make things harder and used different circuits, whatever. It'd be a good thing for credit also.

Good - would like to have it available over a period of time.

S: I wrote in the evaluation that it should progress to something harder. I'd like to go on and if you were continuing with this I'd like, not that I could master this program now that I could find any fault in a matter of seconds or anything like that, but I'd like to go on to something harder. The way you had it all set up into functional blocks for us. You analyzed each block, how they interact, what causes this and that. I'd like to go onto, instead of another power supply, something more complicated. I don't know exactly what. Would you consider a radio more complicated?

Would like to progress to troubleshooting harder instruments.

S: Maybe a TV or an amplifier

S: I don't really know. I don't know what the equipment would be, but something more complicated. I liked it a lot. I liked the format of it.

E: A radio in some sense is actually easier.

S: Yes in some sense.

S: Probably a lot of them. When I first wrote it down I don't know if I wrote it in the program or not. I was thinking along the lines of test equipment and lab equipment that we used in the lab because we have a power supply in our bench.

And we were working with a power supply here. The thing that came into my mind, but it might be too complicated is something like a oscilloscope.

An oscilloscope would be a good instrument to work on.

E: See one of the troubles with a radio or a TV is that they're awfully similar one to another; it doesn't matter what brand it is. There's sort of a standard six transistor radio and there's a standard vacuum tube TV. So there's a set of things you do, if you've ever fixed a few TV's you have some stock things that you know about.

TV's and radios may not be particularly good.

S: And a schematic will get you through.

E: ... It' not just that but if it rolls incessantly, or there's no picture or there's no sound and there is a picture there are these charts and if you've done a little bit of that.

S: You check it out and you go to that place and all this.

E: Yes, and because that's sort of in the common domain, a set of rules like that might make it very hard to find out what motivates the rule.

S: Yes, but you like to understand the logic behind them not just looking down a chart, you know, if this is wrong go to this section and do that. You like to understand why. That's why I liked that expert coming in and explaining what he was doing. You know, what you have done is wrong, and I'll tell you why, it would conflict with this measurement or it would screw up this transistor, or something like that.

Understanding the reasons for replacing parts is important.

S: I know one thing, if I had done it on a day to day basis, like say during the vacation week we had, I would have picked it up a lot faster, because having a week in between also has a week of problems in between. You tend to forget about this until the day you walk in here, you don't even think about it. It's just something, you're still worried about the lab before. So if it were a day to day basis, I would probably pick it up, and if it was straight 8 hours, I know that's kind of impractical, but if it were 8 hours of it I'd really pick it up fast.

One day a week is too spread out.

E: You don't think you'd get saturated with it and want to...

S: Ah, there'd probably be a point where you would get saturated but I think a longer session than 3 hours if I could have kept on maybe 6 hours, without being saturated.	*Could spend twice as long at a session without getting saturated.*
S: Probably tell SOPHIE a few choice words after a while.	
E: Would you guys be interested in participating in future experiments.	*Would you like to do more with SOPHIE?*
S: Oh, definitely	
S: Definitely.	*Definitely.*
S: Very much so.	

Chapter 6

ONE-DAY EXPERIMENT

The Experiment

In order to determine what students could learn from the SOPHIE environment in a highly compact, intense session, we designed a six-hour mini-course which consisted of most of the activities used in the four-day mini-course. In addition to the scheduled sequence of activities we administered a pre- and post-test to assess what was learned during this short exposure.*

The experiment was structured as follows: First students from the same technical institute as the earlier groups agreed to participate in an eight hour troubleshooting experiment to be conducted on a Saturday. They were paid for participating. At 9 o'clock they arrived and were given a brief overview of the day's activities. They were then given the instruction booklet to study for an hour. While studying the booklet, they were encouraged to ask questions and talk over (among themselves) any issues they didn't understand in the booklet. This helped bring everyone up to the same level of understanding. The two experimenters were mostly absent from the study room during this period.

Following the study period, an informal recitation was given covering troubleshooting strategies, feedback circuits and subtle aspects of the IP-28. Then a troubleshooting pre-test was administered using SOPHIE. This test consisted of two exercises, each involving the student locating a fault in the IP-28. In order to minimize any of their anxieties in having to use SOPHIE for the first time and simultaneously take this troubleshooting test, we had each subject write in English on a 3x5 card whatever measurement he wanted to make. The experimenters would then type the question (measurement) into SOPHIE thereby showing him explicitly how to use SOPHIE.** We limited the total time for these troubleshooting exercises to one hour and if the subject was obviously getting nowhere on the first fault, we encouraged him to move onto the second.

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*We consider such a short session to be the least favorable conditions under which to use this system, since this environment has been designed to stress "understanding" as opposed to rote procedure following. Nevertheless we wanted to determine what could be learned under these adverse conditions.

Next there was a lunch break followed by a brief written test which attempted to assess qualitative knowledge of the IP-28. (See Appendix ? for copies of both the pre- and post-tests). The students then engaged in their second SOPHIE activity -- using the Expert Debugger. They used this system for seven runs, inserting a fault in each of the seven functional blocks. After the Expert Debugger located the faulty functional module, they were instructed to pick up where the Expert left off and locate the actual fault inside the given block -- thus providing them with experience with local troubleshooting which complemented the functional block approach of the Expert.

Following this activity they were given a fault to troubleshoot by themselves, without the assistance of the Expert. Then they were split up into two-person teams and given two more faults to troubleshoot. During the team exercises they were encouraged to discuss their troubleshooting strategies and understanding of the IP-28 as much as they wanted.

By this time there was an hour left which was used for a two part post-test. As in the pre-test, they were given two faults to troubleshoot (on an individual basis) and then a written post-test.

Results

Our reactions to the results of the one-day experiment are mixed. On the one hand, we have demonstrated clearly that significant learning takes place in a short time using the extended SOPHIE system. As will be shown below, test scores improved as a result of only three hours of using the system. Further, time to troubleshoot a fault went down dramatically during this short exposure to the system. On the other hand, the students clearly enjoyed the course less than the other three groups did. The one-day people said that their heads were spinning, that we were trying to teach them too much in too little time. Their saturation point had been reached. They felt the experience to be valuable, but too intense.

The written tests were designed to test teleological understanding of the IP-28 power supply. Given symptoms in a particular circuit, students were asked to make hypotheses

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**We now feel that this provides the best way we have yet found to introduce naive users to the system. Usually by the third measurement each subject felt so confident in using SOPHIE that he would disregard our explicit instructions to wait for us and just type in his requests at his own pace.

which would explain the symptoms. Three different circuits were used: a fictitious simple power supply circuit similar to part of the IP-28, a block-diagram IP-28, and an actual IP-28 circuit. Thus, hypotheses in terms of functional blocks and actual component faults were solicited. The tests were intentionally hard enough that no one would get everything -- the test measures a wide range of abilities, and thus no student topped or bottomed out in either pre- or post-tests.

Two tests, designated V and W, were used. They were crossed-over, so that half of the students took V as a pre-test and W as a post-test. The remaining students took the tests in reverse order. Care was taken that students in different groups did not discuss the tests with each other. Crossover allowed us to ensure that pre- and post-tests were of equal difficulty.

Raw scores for the tests were as follows:*

V test: 26.5, 21, 39.5, 23.5
W test: 18, 28.5, 34, 26

Average scores for the two test forms were:

V = 27.6
W = 26.6

Thus, both tests were of approximately equal difficulty.

In terms of pre- and post-tests, raw scores were as follows (of a possible 46 points):

Student	Pre-	Post-	Delta
A	18	26.5	+8.5
B	21	28.5	+7.5
C	34	39.5	+5.5
D	23.5	26	+2.5

All scores improved from pre- to post-test. The mean standard deviation and t-statistic for the Deltas are:

D = +6.00
SD = 2.65
t = 4.54

Thus, at the .95 level of significance, the students improved in their ability to make correct fault hypotheses given a set of symptoms.

The other standard for comparison of student performance we present here is time to troubleshoot a fault using SOPHIE. We compared each student's work on the same fault before and after the bulk of his work with SOPHIE. Note that students had a chance to get used to SOPHIE before the first of these faults. Identity of faults was concealed from the students: The duplicate faults were included with others so that students would be unaware that one fault recurred.

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*One student did not do the post-test.

Times to find the fault were as follows:*

Student	Pre-	Post-	Delta
B	40 minutes	25 minutes	-15 minutes
C	16 minutes	6 minutes	-10 minutes
D	16 minutes	7 minutes	-9 minutes

All students improved dramatically. The average improvement was 11.3 minutes, an improvement of 41 percent. Again, this change is significant at the .95 level.

Qualitative improvement in troubleshooting was also marked. Consider the measurements made by student C in his first attempt [illegible] fault 98 (C6 shorted):

---

*Only three students did the pre- and post-fault test.

Student C
Fault 98 -- First Test

FAULT INSERTED

1. THE OUTPUT VOLTAGE IS -4.7 MILLIVOLTS.
   Reasonable first measurement -- external symptom.
2. THE VOLTAGE AT N5 IS -4.7 MILLIVOLTS.
3. THE OUTPUT VOLTAGE OF THE DC SOURCE IS 49.3 VOLTS.
4. THE VOLTAGE AT N6 IS -4.7 MILLIVOLTS.
5. THE VOLTAGE OF THE CONSTANT CURRENT SOURCE IS 0.0 VOLTS.
   These four measurements represent a signal-tracing approach to the problem. The method has some merit, but it ignores the role of feedback in the circuit. Measurement 4 is inside the Darlington Amplifier, providing little information.
6. THE VOLTAGE AT THE COLLECTOR OF Q4 IS 49.3 VOLTS.
   Redundant -- same test point as measurement 3.
7. THE VOLTAGE AT N3 IS 48.5 VOLTS.
8. THE VOLTAGE AT N2 IS 47.9 VOLTS.
9. THE VOLTAGE AT THE COLLECTOR OF Q2 IS 0.0 VOLTS.
   These three measurements are inside the CCS block, but no evidence of CCS failure has been obtained. (Measurement 5 is inconclusive on this point.)
10. THE OUTPUT CURRENT OF THE CONSTANT CURRENT SOURCE IS -.6 MILLIAMPS.
    This means that the CCS block is OK -- useful information.
11. THE BASE CURRENT OF Q4 IS 0.0 AMPS.
    And that none of the CCS output current is going into the Darlington Amplifier (DA).
12. THE COLLECTOR CURRENT OF Q6 IS 0.0 AMPS.
    Or into the Current Limiter (CL),
13. THE COLLECTOR CURRENT OF Q5 IS 0.0 AMPS.
    Or into the Voltage Limiter (VL).
14. THE CURRENT THRU C6 IS .61 MILLIAMPS.
    Only remaining place for the current to be going. Confirming (unnecessary) measurement.

C6 REPLACED

15. THE OUTPUT VOLTAGE IS 30.1 VOLTS.
    Verifying that the symptom has been eliminated.

Student C

Fault 98 - Second Test

FAULT INSERTED

1. THE VOLTAGE IS -4.7 MILLIVOLTS.
   Reasonable -- observe external symptom, as before.
2. THE OUTPUT VOLTAGE OF THE VOLTAGE REFERENCE SUPPLY IS 29.0 VOLTS.
   Good functional measurement -- checking the voltage regulation mechanism.
3. THE OUTPUT CURRENT OF THE CONSTANT CURRENT SOURCE IS -.6 MILLIAMPS.
   Good functional measurement -- is there current for the feedback regulation mechanism to operate.
4. THE BASE CURRENT OF THE DARLINGTON IS 0.0 AMPS.
   Is any of this current going to the Darlington Amplifier, as it should be?
5. THE BASE CURRENT OF Q6 IS 0.0 AMPS.
   Probably meant collector of Q6 -- mistyped?
6. THE COLLECTOR CURRENT OF Q5 IS 0.0 AMPS.
   Is it going into the Voltage Limiter?
7. THE CURRENT THRU C6 IS .61 MILLIAMPS.
   Confirming measurement -- must be shorted capacitor.
8. THE MEASURED RESISTANCE OF C6 IS 0.0 OHMS.
   Second confirming measurement -- apparently just trying a new question.

C6 REPLACED

9. THE OUTPUT VOLTAGE IS 30.1 VOLTS.

The above scenarios show a dramatic qualitative improvement. The first is characterized by a lack of overall strategy and an insensitivity to the teleology of the instrument. The second is much more systematic, showing the clear influence of the Expert Debugger. Measurements are at the inputs and outputs of functional blocks until the location of the fault becomes clear. Measurements inside working blocks have been completely eliminated.

Chapter 7

CONCLUSION

We have described here a set of extensions to the SOPHIE system, the structure of a short course in electronic troubleshooting, and a series of formative experiments to evaluate the one in the context of the other. We have shown by example that sophisticated artificial intelligence-based systems and frame-oriented systems can complement each other to good advantage. We have constructed a learning environment which is rich, open ended, and at the same time structured in a way which makes it easily exploitable.

We believe that each of the components of the learning environment presented here has been shown to be of value. The written lesson materials described in Chapter 2 were very well received, providing a solid basis upon which to build the remainder of the troubleshooting and electronics course. The two team troubleshooting games were extremely successful, as was the expert debugging interaction.

Lesson Materials

Our students in the experiment praised the written lesson material highly. We are developing a theory of presentation for teleological knowledge. The lesson material represents our attempt to use our evolutionary design metaphor for communicating how and why a circuit is structured the way it is. In future work, we hope to refine and better articulate this theory so that it can be applied more generally.

Two-Team Game

The two-team troubleshooting game was successful in two ways. First, it proved to be an effective learning situation. The students took readily to the competitive aspect of the game, increasing their already high motivation. Competition in the game is a tool which allows us to direct student attention to areas of the interaction we wish to stress. In particular, inventing devious faults is a productive activity. It exercises all of the student's knowledge of the teleology and symptomatology of the instrument. Similarly, having to set up the instrument's controls to evidence a symptom calls on one's ability to predict consequences of faults. By adjusting the rules of the two-team game, we have been able to emphasize just those activities which we consider most useful in extending the depth of student understanding.

The second success of the two-team game is that it gives us new access to the thinking of students as they develop their own models of electronics and troubleshooting. Before discovering this method, we had relied on protocol analysis and the introspective reports of troubleshooters. Unfortunately, introspection usually does not yield good information about misunderstandings or even strategy. By recording a pair of students working on a fault, we get a great deal of highly useful information. Team players are far less self-conscious than single "informants." They make and defend hypotheses, explain things to each other, and plan strategies. We plan to use this method of viewing students' developing world models extensively, in conjunction with debugging protocols, to develop more refined automated procedures for diagnosing and correcting student errors and misunderstandings in the learning environment.

Expert

The expert debugging interaction, similarly, is a productive augmentation of the basic SOPHIE lab environment. Well received, it gives student exposure to an articulate and proficient debugger. Students found the interaction to be interesting and revealing of general troubleshooting strategy and of the characteristics of the instrument under test. The Expert is implemented using a carefully built debugging tree, augmented by text frames which explain strategy, logic, and conclusions. As such, it represents an advanced, frame-oriented CAI sub-system. Such frame-oriented programs can be integrated into a larger environment which contains sophisticated AI-based programs, games, and other activities. The Expert Debugging Interaction provides activities in the SOPHIE environment which complement the laboratory. The two activities, in combination and alternation, are more effective than either would be alone. The Expert provides a directive introduction to how to troubleshoot and how to make use of the SOPHIE lab. The lab, on the other hand, provides situations which challenge the student's debugging and electronics understanding, making what the Expert has to say more interesting and relevant.

Although in its current implementation the Expert is a purely extensional system, we are developing a generative version which promises to be far more flexible. This development is only possible because of the experience gained in building the extensional system first. The generative system we are building will adapt to the state of knowledge and comprehension of the student. It will be implemented using production rules, a technique which promises substantial flexibility. Although some of the texts printed by the new system will be "canned," the remainder will be generated. We hope that many of the explanations we provide will be synthesized as needed, using advanced models of how to explain circuit interactions and debugging strategy.

The Expert sub-system is expected to scale up well. The complexity of circuit and strategy which can be built into an extensional system is limited by practical considerations -- one has to write a great deal of text and think out a large number of contingencies. Our generative system, however, should be able to cope with more complex circuits and a range of debugging strategies. We expect that the new system will be able to deal with a variety of circuits, and will not be limited to DC analysis. The logic employed can be applied as easily to AC circuits, circuits in which transients, distortion, waveforms, and noise are important, and to other technologies such as digital circuitry and microwaves.

Finally, the Expert system is susceptible to scaling down as well as up. Since the faults which it introduces into the circuit can be a finite, pre-determined set without damage to the interaction, circuit simulations could be pre-computed instead of generating them on-the-fly, as is done now. The demands upon computing resources which remain are so modest that the resulting system could be implemented easily on a small computer with sufficient file access. We plan to experiment in this dimension as well. One configuration which we have considered employs an intelligent terminal to execute the Expert program. File storage could be provided on-line to the terminal, or via a time-shared interaction with a larger host. Such a configuration could be very economical immediately.

Mini-Courses

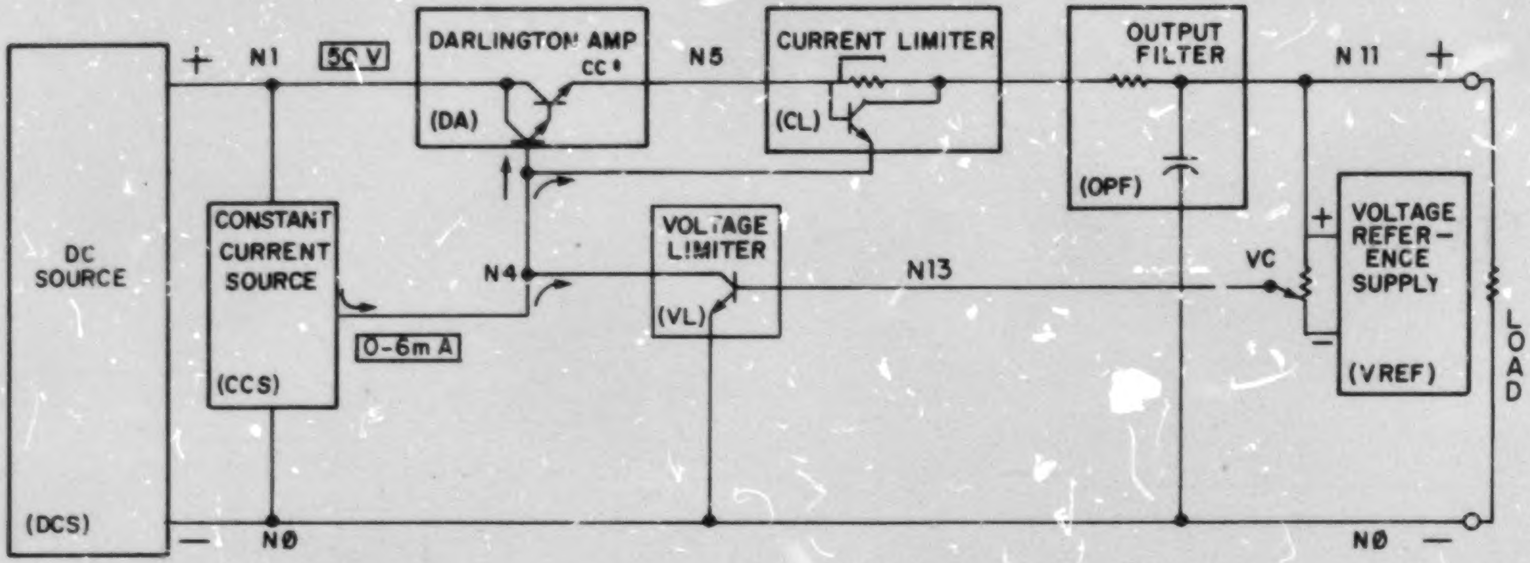
Several conclusions may be drawn from the formative learning experiments performed in the extended SOPHIE environment. By experimenting with format, we have determined that a single, concentrated exposure to our troubleshooting and electronics material may well be a poor way to teach it. Instead, a somewhat longer exposure, spread out over a greater elapsed time, seems to be more effective. The experience of the SOPHIE environment may in fact induce a major reorganization of the student's understanding of electronics and debugging. Such a shift of model takes time to assimilate. Thus, a single day concentrated exposure is inappropriate. Rather, a day a week for several weeks, or a few hours a day for several days seems to be a preferable schedule.

An important area of concern to us is the role of instructors in a SOPHIE-based learning environment. We believe that a well designed system will allow the lab instructor to change the way he interacts with his students. The computer system is able to help students pinpoint their own problems by example (the Expert) and by explicit counter-example (lab hypothesis evaluation). Thus, the lab instructor is not required to track each student's measurements. Instead, when a student is having trouble, the instructor can make use of SOPHIE facilities to point to areas which need further explaining, or suggest SOPHIE activities to the student to shed light on his problem. For example, the instructor might recommend that a student experiment with an instrument with a particular fault before proceeding with his immediate problem. SOPHIE's greatest weakness at the moment is that it cannot follow up on errors or hypothesis evaluations. One of the roles of an instructor in the SOPHIE environment is to provide this kind of followup, and to suggest particular activities within the environment which he thinks will be beneficial.

Thus, the instructor plays an essential role in the total learning environment. To be able to carry out his part, the instructor must be a competent troubleshooter. He must have a good intuitive feel for the electronics involved in the instruments under consideration. The SOPHIE environment allows him to be of more service to more students than he would otherwise be. But because he is responsible for clearing up misunderstandings beyond the scope of the computer system, the success of students in the lab who are having the most difficulty will depend heavily on him.

Much to our surprise, several students commented that they thought the mini-course taught logical skills beyond those of troubleshooting, per se. They thought that general problem-solving strategies were being learned. In particular, we were using a high level model approach which proceeds by decomposing whole systems into functional units. The interactions of these components reflect both their own implementation at a lower level and the behavior of the system at a higher level. Viewed in these terms, the troubleshooting and model-building experience gained with SOPHIE may in fact be applicable in many other domains.

APPENDIX A IP-28 Diagrams


DC SOURCE
(DCS)
+
N1
50 V
DARLINGTON AMP
CC*
(DA)
N5
CURRENT LIMITER
(CL)
OUTPUT FILTER
(OPF)
N 11
+
CONSTANT CURRENT SOURCE
(CCS)
0-6mA
N4
VOLTAGE LIMITER
(VL)
N13
VC
+
VOLTAGE REFER-ENCE SUPPLY
(VREF)
−
LOAD
−
NØ
NØ
−

CURRENT RANGE (CR)	OUTPUT CURRENT-LIMIT RANGE	
	(CC=0)	(CC=1)
LOW	0.001 A	0.1 A
HIGH	0.001 A	1.0 A

VOLTAGE RANGE	OUTPUT VOLTAGE RANGE	
	VC=0	VC=1
LOW	1	10
HIGH	1	30

* VC SHOWN SET TO MAXIMUM (1.0)
CC SHOWN SET TO MAXIMUM (1.0)

IP-28 FUNCTION BLOCK DIAGRAM

FIG. A1

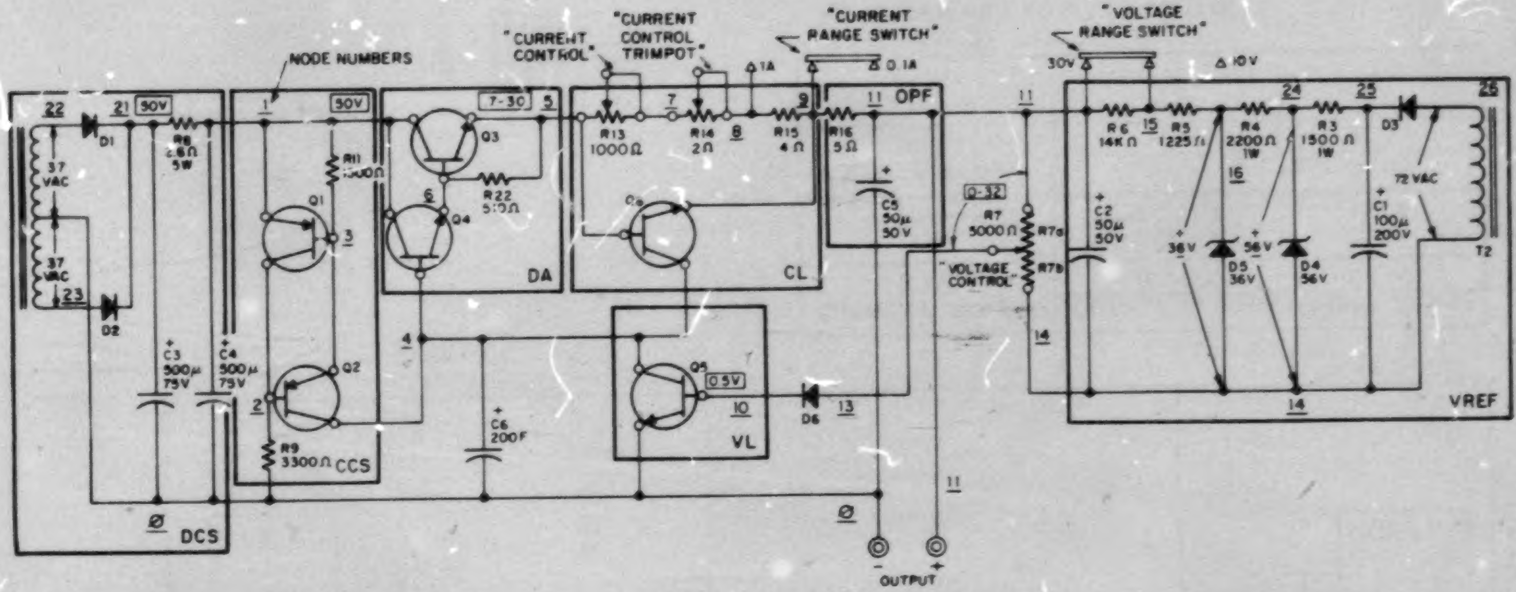

NODE NUMBERS
"CURRENT CONTROL"
"CURRENT CONTROL TRIMPOT"
"CURRENT RANGE SWITCH"
1A
0.1A
"VOLTAGE RANGE SWITCH"
30V
10V
22
21
30V
23
37 VAC
37 VAC
D1
D2
R8 2.8Ω 5W
C3 500µ 75V
C4 500µ 75V
0
DCS
1
50V
R11 1500Ω
Q1
3
Q2
2
R9 3300Ω
CCS
7-30
5
Q3
6
Q4
R22 510Ω
DA
4
C6 200F
R13 1000Ω
7
R14 2Ω
8
R15 4Ω
9
Q6
CL
Q5
0.5V
10
VL
D6
13
R16 5Ω
11
OPF
C5 50µ 50V
0
11
OUTPUT
11
0-32
R7 5000Ω
R7a
R7b
"VOLTAGE CONTROL"
14
C2 50µ 50V
R6 14KΩ
15
R5 1225Ω
R4 2200Ω 1W
16
24
R3 1500Ω 1W
25
26
36V
D5 36V
56V
D4 56V
C1 100µ 200V
D3
72 VAC
T2
14
VREF

FIG. A2. IP-28 SCHEMATIC

APPENDIX B Lesson Materials

I. INTRODUCTION

The power supply which you will learn in this lesson is the Heathkit IP-28, a good example of an electronically regulated, solid state, laboratory power supply.

The approach used here in explaining how the IP-28 functions will be to start with a broad general description of the requirements that must be met by circuits which are to behave as a power supply and to progress in stages to an explanation of the actual circuits used in the IP-28.

In the intermediate stages we'll describe the circuits as functional modules which do specific jobs. These functional modules are the "blocks" of the block diagrams with which you may be familiar. After considering the functional structure of the IP-28, we shall consider circuit details, first by looking at simple circuits, and, finally, by developing these circuits into the actual working electronics of the IP-28.

II. BASIC REQUIREMENTS OF A REGULATED POWER SUPPLY

The primary function of a power supply is to change the alternating current of power utilities to direct current. You probably already know that this conversion is accomplished by a rectifier which changes alternating current into pulses of unidirectional current followed by a filter which smooths out these pulses into a steady direct current.

A rectifier and filter can thus be thought of as a power supply, as shown in the functional diagram of Fig. 1.

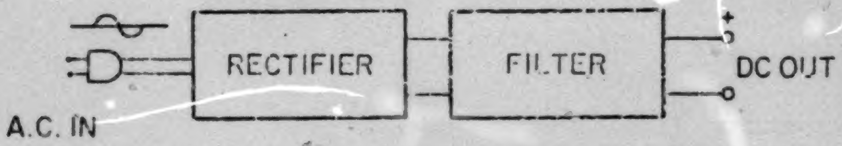


FIG. 1

113

But this type of rectifier filter combination is by itself very unsatisfactory because its DC output is not very steady. It changes under the influence of many external factors such as amplitude of input AC voltage, temperature, and, particularly, as the load current changes. Since modern electronic equipment requires very steady voltages, a sophisticated power supply like the IP-28 needs to have additional circuits to stabilize the voltage provided by a simple rectifier and filter, and to provide the facility to vary it. These additional circuits are called the power supply's *regulator*. Fig. 2 is a functional diagram of a *regulated* power supply.

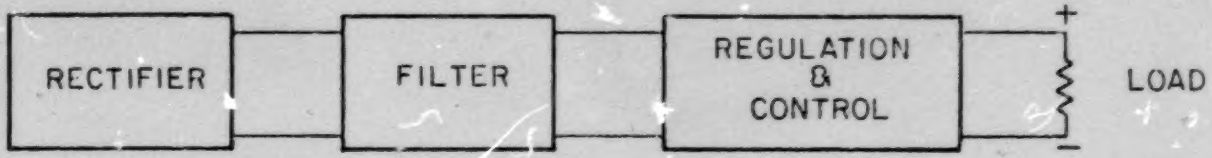


FIG. 2

Most of the complexity of the IP-28 resides in these functions of regulation and control, so let's begin by taking a first look at how a regulator works.

REGULATORS

There are many kinds of regulators. We shall be concerned mainly with a class of regulators called *active* regulators. This is because they maintain the supply's output voltage constant by actively *doing* something. If, for any reason, the output voltage departs from its nominal or required value, these types of regulators *react* in a manner which returns the output voltage to where it should be. It is clear that in order to accomplish this *active* adjustment of output voltage to compensate for perturbations caused by changing load and other factors, regulators must be able to do two things.

First the regulator must be able to somehow vary the output voltage. Second, the regulator must be able to sense any deviation of the output voltage from its required value. These two functions are performed by most if not all regulated power supplies. There are many ways of implementing these functions, each leading to a particular classification of regulator such as "series regulator", "shunt regulator", "switching regulator", etc. Perhaps you have heard about these.

In this lesson we shall consider only the Series regulator or Series-pass Regulator because the IP-28 is an example of this particular type. In the next section we shall see why it is so called.

We have already mentioned that a regulator must be able to vary the output voltage of the supply. The regulator accomplishes this variation by means of a REGULATING ELEMENT. In Fig. 3 below is shown a typical way of using a regulating element to vary the output voltage of a supply.

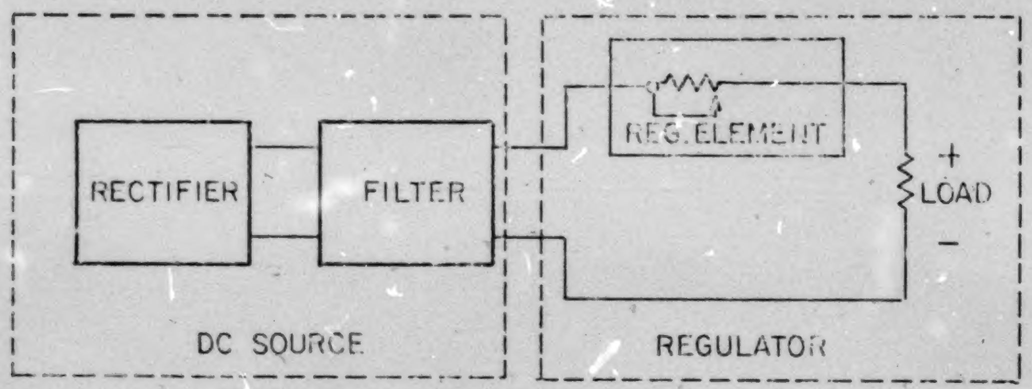


FIG. 3

As you can see, the regulating element is shown as a variable resistance placed in series with the load. This series arrangement is the reason why such a regulator is called a Series regulator. By varying the effective resistance of its regulating element, the Series regulator is thus able to vary the voltage delivered at the load according to the laws of simple voltage divider action.

Fig. 3 is incomplete as a basic functional description. It does not show how the regulating element is controlled. Obviously there is no little man inside the supply cranking the slider of a rheostat. There are, however, circuits which do this job of controlling the regulating element, and, for the moment we shall lump them all into a function called the CONTROLLER.

Now, how does the CONTROLLER know that the output voltage has strayed and needs readjusting? The answer is simple. It is told by another function which senses the output voltage and compares it to a REFERENCE voltage. Fig. 4 shows these additional functions.

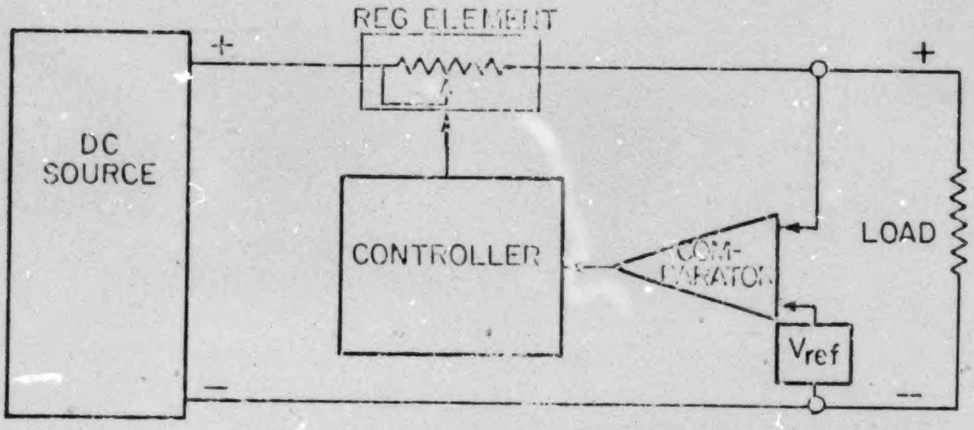


FIG. 4

We are now in a position to summarize briefly the basic operation of a series regulated supply. Please refer to Fig. 4.

The rectifier and filter change AC voltage into a DC voltage which is applied to the load through a series REGULATING ELEMENT whose effective resistance can be adjusted. A COMPARATOR senses the output voltage source Vref. If there is a difference between the two, a CONTROLLER adjusts the REGULATING ELEMENT until that discrepancy disappears. This feedback action is continuous and thus dynamically maintains the output voltage at the desired value.

Having summarized the functional relation of series regulated supplies in general, we are now ready to develop the basic modules which make up the IP-28.

FUNCTIONAL MODULES
SIMPLIFIED CIRCUITS

Having understood the underlying structure of the IP-28, we can now proceed to a preliminary version incorporating actual circuits.

Fig. 5 shows a first realization of a power supply built along the lines suggested by the basic functional block diagram of Fig. 4. The circuits shown in Fig. 5 are simplified versions of the real ones found in the IP-28 but they work nevertheless and are useful as an introduction to their more complex counterparts. The actual circuits of the IP-28 do not differ in principle, but are more complicated only for reasons of increased performance, overcoming limitations of individual components, adding protection,etc. We'll be getting to these circuits later, but for the moment let's look at the ones shown in Fig. 5.

THE SERIES REGULATING ELEMENT

The regulating element of our simplified power supply is a single transistor Qr. Its collector is connected to the output of the filter and its emitter toward the load. The collector-emitter resistance of Qr is thus placed in series with the load. Since it is a property of a transistor operating in its active region that its collector emitter resistance varies as the base current is changed, Qr behaves effectively as a variable resistor whose resistance is controlled by a current. As the base current Ib of Qr varies, the voltage drop from the collector to the emitter changes and consequently, the voltage applied to the load changes according to a simple voltage divider action. We have then our means of controlling the output voltage of the power supply. Now, it is important to realize that while Qr does indeed behave like a current controlled variable resistance, it nevertheless must still conform to the requirements of any transistor operating in its active region as an amplifier. Thus, in a non-faulted functioning circuit, Qr has its base-emitter junction forward biased, its collector-base junction reverse biased, and its collector current related to the base current by:

$$\frac{Ic}{Ib} = \beta$$

where β= dc current gain. (Remember this when you begin to troubleshoot the IP-28.)

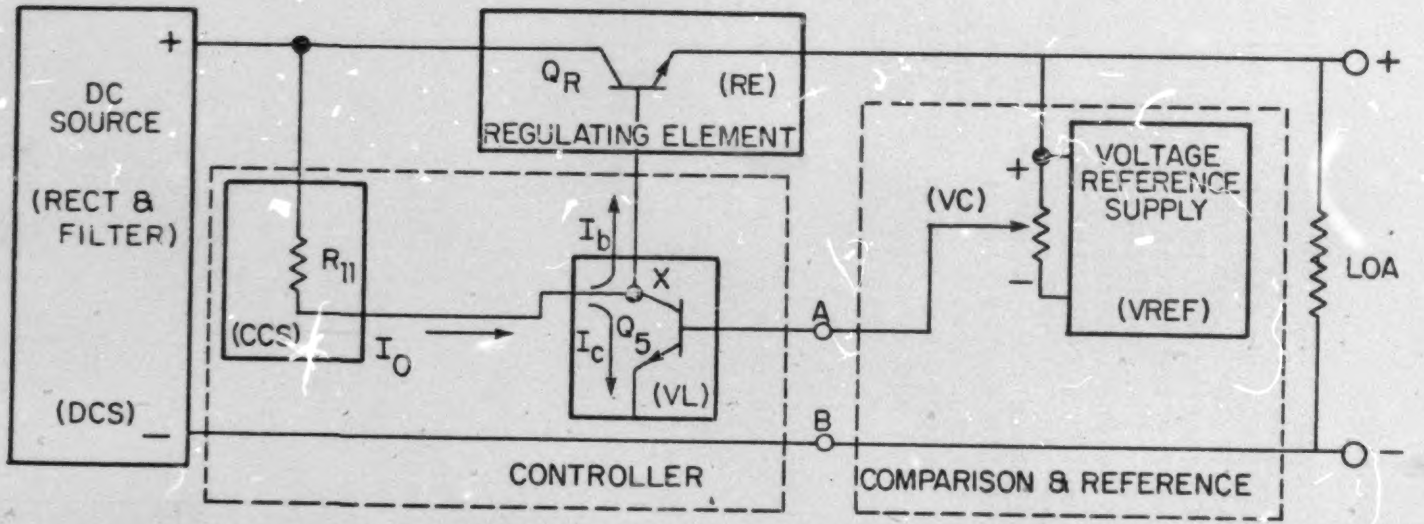

DC SOURCE
(RECT & FILTER)
(DCS)
+
−
R_{11}
(CCS)
I_O
Q_R
(RE)
REGULATING ELEMENT
I_b
X
I_c
Q_5
(VL)
CONTROLLER
A
B
(VC)
+
−
VOLTAGE REFERENCE SUPPLY
(VREF)
COMPARISON & REFERENCE
LOA
+
−

FIG. 5

COMPARISON AND REFERENCE

Before we discuss the CONTROLLER which varies the collector-emitter resistance of Qr, let's see, with reference to Fig. 5, how an error or discrepancy signal is generated in the IP-28. This error signal you will recall is what tells the controller to readjust the regulating element Qr in a way which brings the output voltage back to its required value. The functional block diagram of Fig. 4 shows the error signal being generated by a mysterious comparison block which accepts the output voltage and the reference voltage as inputs, and which outputs an error signal, presumably when the output voltage of the power supply does not match the reference voltage. In the IP-28, the comparison between output and reference voltages is performed in a deceptively simple fashion: output voltage and reference voltage are subtracted from one another by simply "bucking" them, that is, by placing them in series with one another.

It may be easier to see this if we redraw the pertinent portion of Fig. 5 to obtain Fig. 6 on the following page. Now it is clear from Fig. 6 that Vab, the voltage between nodes A and B which is applied to the controller, is just the difference between reference voltage Vref and output voltage, Vload. Therefore, when the output voltage rises above Vref, Vab becomes positive and drives the controller. The latter in turn adjusts Qr as we shall see shortly.

REFERENCE VOLTAGE SOURCE VREF

The primary requirement for Vref in this application is that it be isolated or "floating". A battery having the required voltage would be suitable and could in fact be wired into a circuit. Batteries do run down, however, so in the IP-28 Vref is a complete power supply all by itself. It has a transformer, a rectifier, a filter, and of course a regulator! For our simplified power supply it is enough to have Vref consist of the crudest type of half-wave rectifier, capacitor, and zener diode as a passive regulating element. This is shown below in Fig. 7.

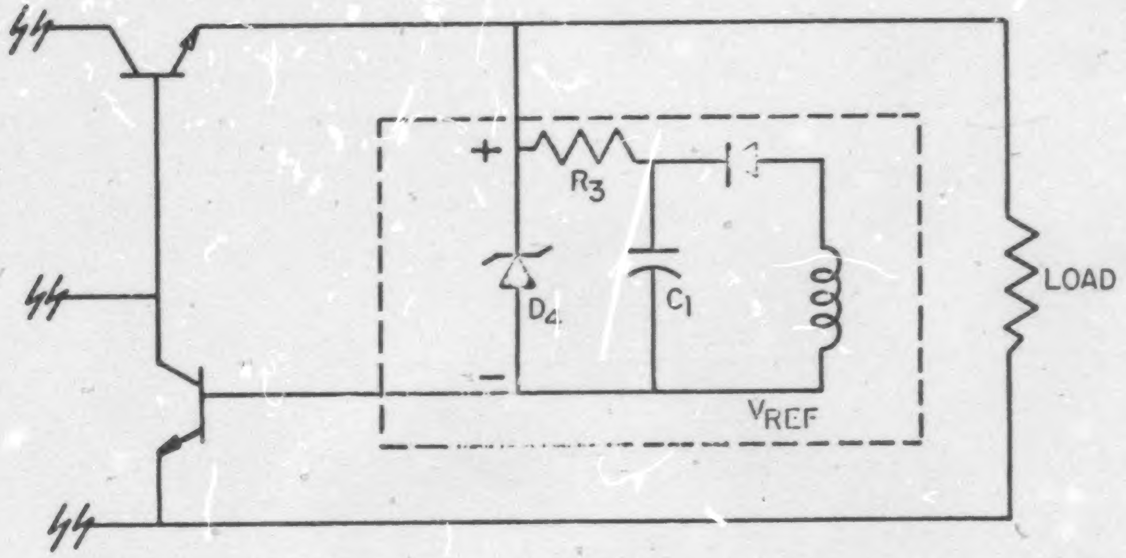

+
R3
D4
C1
−
VREF
LOAD

FIG. 6

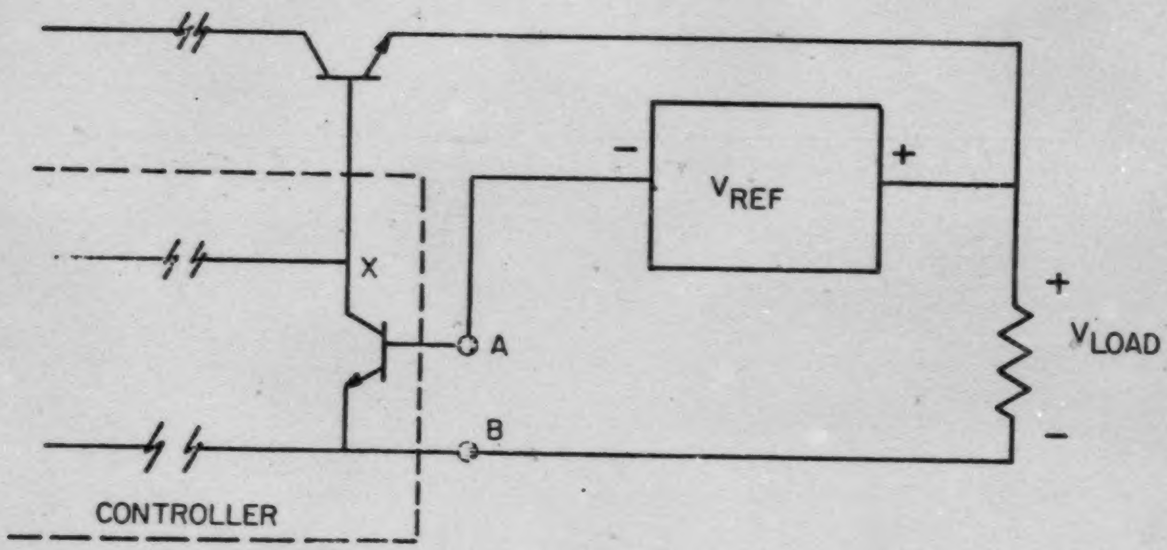


FIG. 7

CONTROLLER

As we have seen, Vab is the result of the comparison function. It is the job of the controller to accept Vab as input and to translate this into a suitable compensating drive for Cr, the regulating element. Reference to Fig. 5 shows the controller to be made of a CONSTANT CURRENT SOURCE, consisting (for the time being) of only R11 and of a control transistor Q5. We shall make these two components into two separate functional modules, the CC (for Constant Current Source) and the VL (for Voltage Limitter). The purpose of the constant current source is to maintain an unvarying current Io flowing into junction X. We shall postpone a discussion of how a good constant current works. For the moment we just assume that a relatively stable current flows out of R11. It is important at this stage to realize that Io should never change in a [illegible]perly functioning circuit. Now notice that Io flows into junction X and divides into two currents Ib and Ic. If transistor Q5, the VL, is off, all of Io flows in the upper branch. This condition presents the maximum drive to Qr, causing the latter's effective resistance to be the lowest possible. It is also the condition under which the power supply delivers its maximum current to the load. When Q5 begins to conduct as a result of positive drive voltage Vae being applied to its base, a portion of Io is diverted away from the base of Qr resulting in less drive to that transistor and a consequent increase in its collector emitter resistance. The controller thus functions by using the input voltage Vae to vary the conduction through Q5 which in turn shunts current away from the base of Qr.

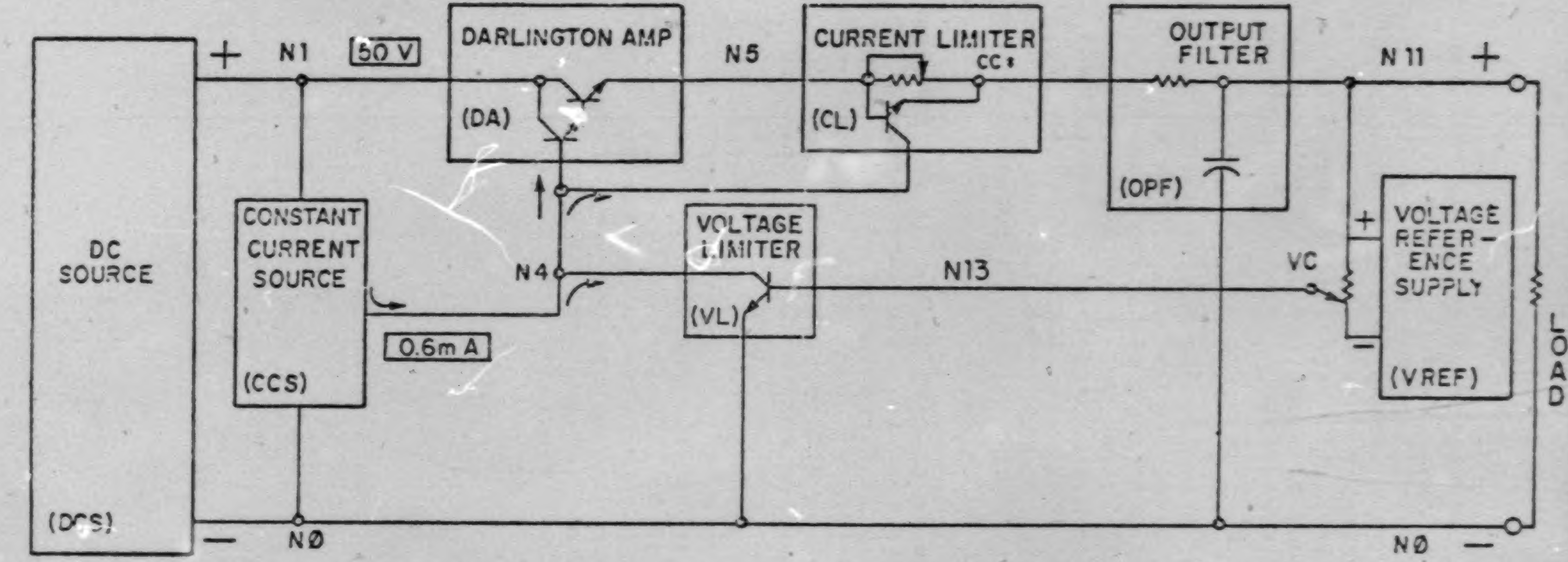
We have just discussed the circuits making up the major functional blocks of our simplified IP-28. These are: the Direct Current Source (DCS) made of a rectifier and filter (which we won't describe since you are probably quite familiar with these), the series regulating element (RE), the constant current source (CCS), the Voltage Limiter (VL), and the reference voltage source (Vref). Now we can summarize the operation of the IP-28 in terms of these circuits. Please refer again to Fig. 5.

Unregulated DC voltage is applied to the load through the collector-emitter path of Qr, the series-regulating transistor. When the supply is first turned on, the output voltage is zero and therefore less than the reference voltage Vref. Vab is negative and Q5 completely cut off. All of Io thus flows into the base of Qr. At some point, the output voltage becomes greater than Vref. At some point, the output voltage becomes greater than Vref causing Vab to become positive. Qc begins to conduct and shunts current away from the base of Qr. The voltage drop across the collector and emitter of Qr increases as a result of the decrease in base drive Ib and continues to decrease until the output voltage stabilizes at some value very close to Vref. Henceforth, the output voltage remains equal to Vref and the regulating action just described acts continually to maintain it at that value.

FUNCTIONAL MODULES
THE REAL IP-28

By now you should be thoroughly comfortable with the concepts involved in the simplified IP-28, so it is time to consider the "real", more complex IP-28. Fig. 8 is a more accurate functional description of the actual IP-28. You'll notice that there are two additional functional blocks included, namely the CL and the OPF. Fig. 9 is the schematic of the IP-28 and shows the complete circuits inside each module.

The "real" IP-28 has:
..... a more complex regulating element


DC SOURCE
(DCS)
+
−
N1
50 V
DARLINGTON AMP
(DA)
N5
CURRENT LIMITER
CC‡
(CL)
OUTPUT FILTER
(OPF)
N 11
+
CONSTANT CURRENT SOURCE
(CCS)
0.6m A
N4
VOLTAGE LIMITER
(VL)
N13
VC
+
−
VOLTAGE REFERENCE SUPPLY
(VREF)
LOAD
N0
N0
−

CURRENT RANGE (CR)	OUTPUT CURRENT-LIMIT RANGE	
	(CC=0)	(CC=1)
LOW	0.001 A	0.1 A
HIGH	0.001 A	1.0 A
VOLTAGE RANGE	**OUTPUT VOLTAGE RANGE**	
	VC=0	VC=1
LOW	1V	10 V
HIGH	1V	30 V

‡VC SHOWN SET TO MAXIMUM (1.0)
CC SHOWN SET TO MAXIMUM (1.0)

FIG. 8

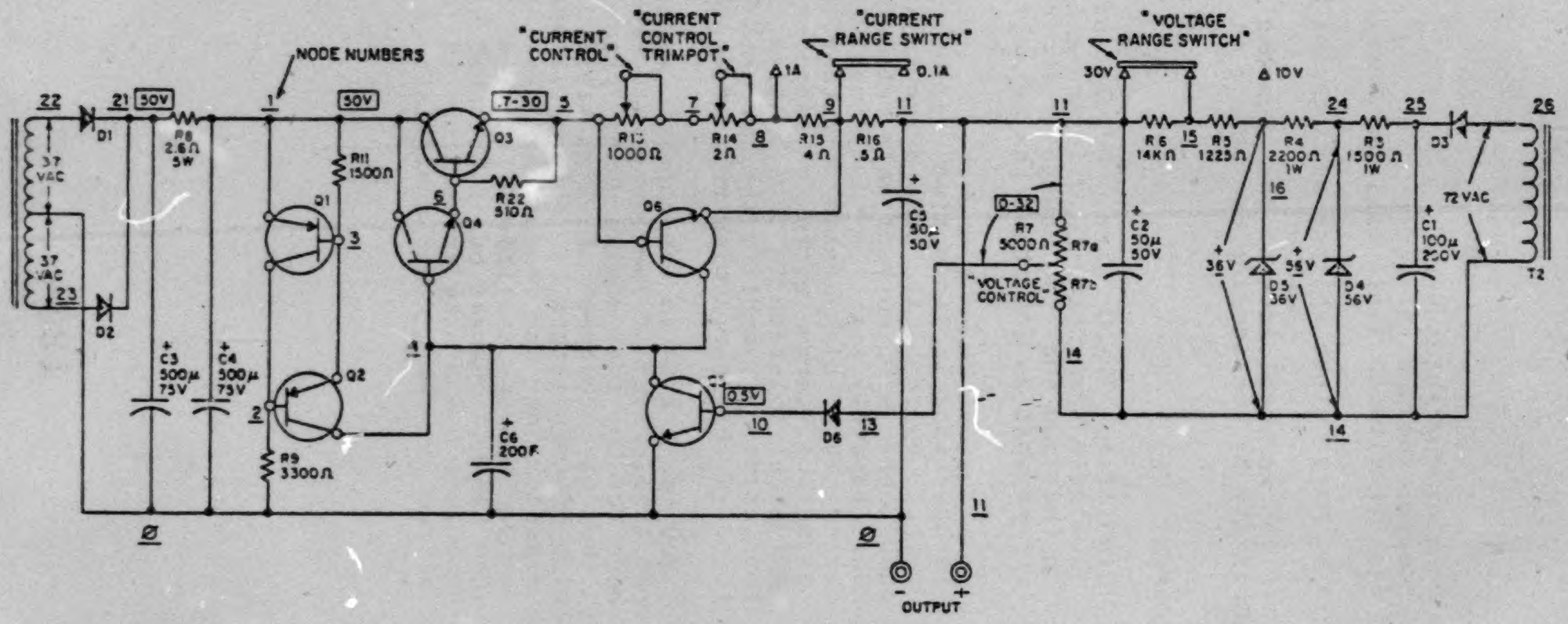

NODE NUMBERS
"CURRENT CONTROL"
"CURRENT CONTROL TRIMPOT"
"CURRENT RANGE SWITCH"
"VOLTAGE RANGE SWITCH"
1A
0.1A
30V
10V
22
21
50V
1
50V
.7-30
5
7
8
9
11
11
15
16
24
25
26
23
3
6
2
4
10
13
14
14
11
Ø
Ø
37 VAC
37 VAC
D1
D2
R8 2.6Ω 5W
R11 1500Ω
R9 3300Ω
R22 510Ω
R13 1000Ω
R14 2Ω
R15 4Ω
R16 .5Ω
R6 14KΩ
R5 1225Ω
R4 2200Ω 1W
R3 1500Ω 1W
C3 500μ 75V
C4 500μ 75V
C6 200F
C5 50μ 50V
C2 50μ 50V
C1 100μ 200V
Q1
Q2
Q3
Q4
Q5
Q6
0.5V
D6
0-32
R7 5000Ω
R7a
R7b
"VOLTAGE CONTROL"
36V
56V
D5 36V
D4 56V
D3
72 VAC
T2
OUTPUT
-
+

FIG. 9

..... a more complex current source
..... a more complex voltage reference
..... protective circuits to limit maximum current out of supply
..... controls to vary output voltage and current limits

In the next section we shall look at the reasons for this increased complexity by considering one module at a time.

REGULATING ELEMENT (DA)

In the simplified IP-28 the regulating element consisted of a single transistor Qr. If the supply had to deliver 1 amp to the load and the output of the current source were .6 ma what do you think the beta of Qr should be?

Since Qr is operating in its active region, the ratio of required output current to base drive is about 1666. Therefore Qr should have a DC current gain beta of at least that much. Unfortunately, it is not possible to find transistors having such high betas together with the capacity to pass the large currents necessary in this application. A typical solution to this problem is to use an additional transistor to amplify the current and this is what is done to solve this particular problem in the IP-28.

In Fig. 9 you can see Q4 as the current amplifier for control current issuing out of the constant current source. The drive current for Q3, the series pass transistor, is thus roughly the base current of Q4 multiplied by its B. Such a connection of transistors to obtain larger current gain is a classic one and known as the "Darlington connection" or Darlington amplifier. Notice that the addition of Q4 has not changed our functional view of the IP-28; in fact, unless one of the transistors is faulted you can treat the two like you would a single transistor, as shown in Fig. 10.

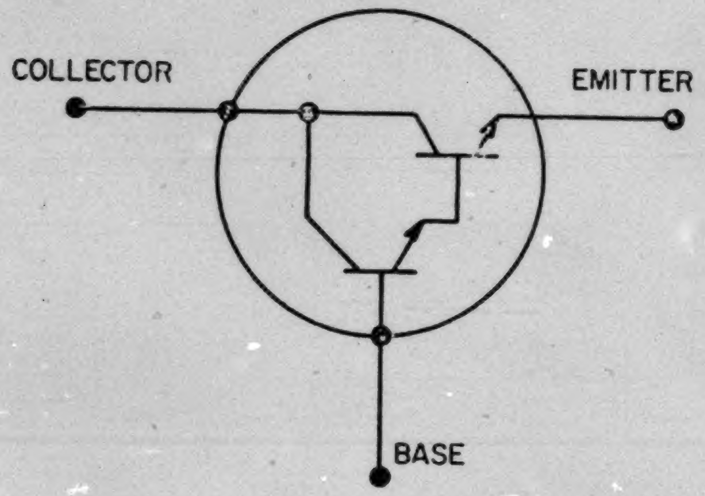


FIG. 10

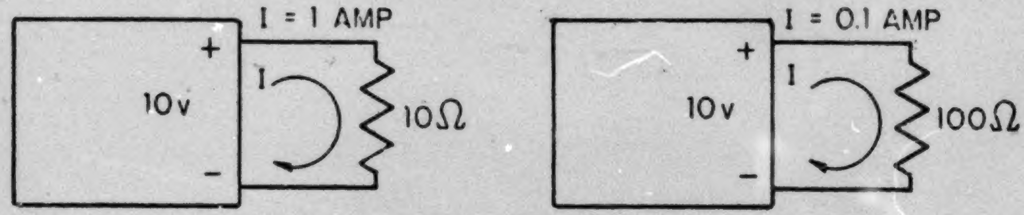
Because of this "Darlington" connection of two transistors to form the regulating element, we have renamed this functional module the DA. In the schematic, Fig. 9, you'll notice a few complications. R22 is added to keep the base-emitter junction of Q4 forward biased or "on" when the supply is very lightly loaded. Simple? Yes, but be forwarned. There are subtle faults with strange symptoms which can develop here. You might explore these possibilities by asking Sophie to fault this region (perhaps R22) and making measurements.

CONSTANT CURRENT SOURCE (CCS)

A glance at the schematic shows that the CCS, made up of two transistors, Q1 and Q2, is considerably more complicated than the CCS of the simplified supply which consists of a single resistor R11.

However, before explaining the reasons for this considerably increased complexity, it may be useful to pause in our explanation of the functional modules in order to discuss current sources. We did not say much about them earlier.

What are current sources? Current sources are completely analogous to voltage sources but they do not appear as frequently in our environment as voltage sources do, so they may seem strange at first. An ideal voltage source delivers the same voltage to a load regardless of the load's value. Fig. 11 summarizes the behavior of a voltage source.



10 volt voltage source delivers 1 amp to 10 ohm load.

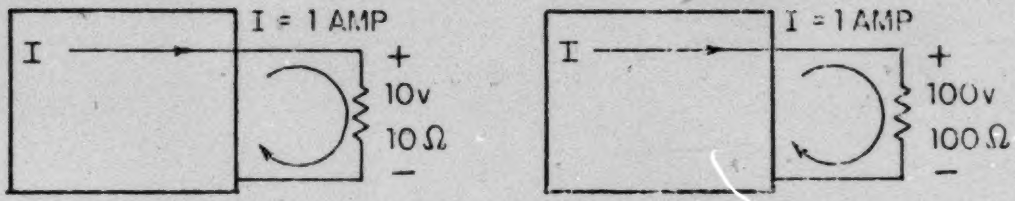
a)

When the load is changed to 100 ohms, the voltage source delivers 0.1 amp. The voltage output remains at 10 volts.

b)

FIG. 11 VOLTAGE SOURCE BEHAVIOR

In an analogous fashion, an ideal current source delivers the same current to a load regardless of the value of the load. This is shown in Fig. 12.



1 amp current source delivers 1 amp through 10 ohm load. Voltage developed across load is 1x10 = 10 volts.

a)

When the load is changed to 100 ohms, the current source continues to deliver 1 amp. The voltage across the load now rises to 100 volts!

b)

FIG. 12 CURRENT SOURCE BEHAVIOR

Most sources of electrical power are voltage source. Batteries, power supplies, household outlets, etc., are all voltage sources and exhibit characteristics summarized in Fig. 11. If that is so, how does one make or obtain a current source?

One way, perhaps the simplest, is to deliver power from a voltage source to a load through a resistor that is very much larger than the load itself as shown in Fig. 13.

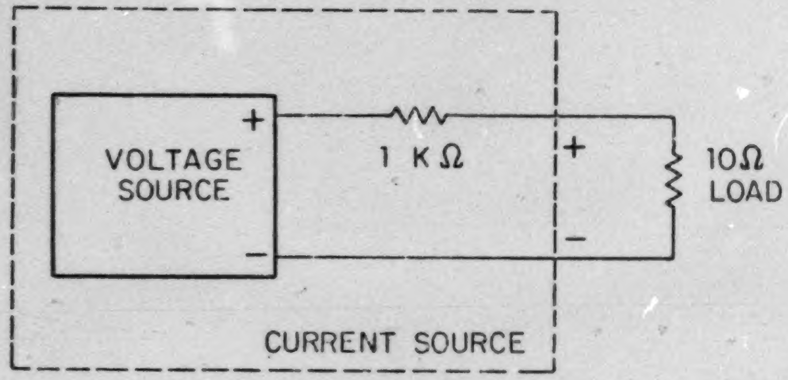


FIG. 13

The current in the circuit above is primarily determined by the 1K resistor because the load is so small. If we change the load from 10 ohms to 15 ohms for instance, the current won't change very much, so it appears that the 10 ohm resistor is driven primarily by a current of 1 ma.

This is the approach taken in the "simple" version of the IP-28 (Fig. 5) in which the CCS consists of a single resistor R11. Of course, this method of creating a current source has disadvantages. It does not create a truly unvarying source of current, and the large resistor causes a correspondingly large voltage drop which results in a very small current output and requires a very large voltage source to start with.

Fortunately there are better ways to make current sources. In fact, an ordinary transistor biased as a linear amplifier behaves as a current source for its collector load resistor. This is true because the collector current is determined by the transistor's emitter-base bias, and, *within certain limits*, nothing one does to the collector load resistance can change the collector *current*.

The reason for this is inherent in the way a transistor works. You probably recall from elementary transistor theory that the collector current is due almost entirely to carriers which have been injected into the base region of the transistor by forward biasing its emitter base junction. These carriers have a polarity which causes them to be "swept" into the collector circuit by the collector-base bias voltage, and their flow through the collector is what we call the collector current. The collector current is thus controlled only by the biasing of the emitter base junction. This inherent characteristic of the transistor is shown graphically in Fig. 14.

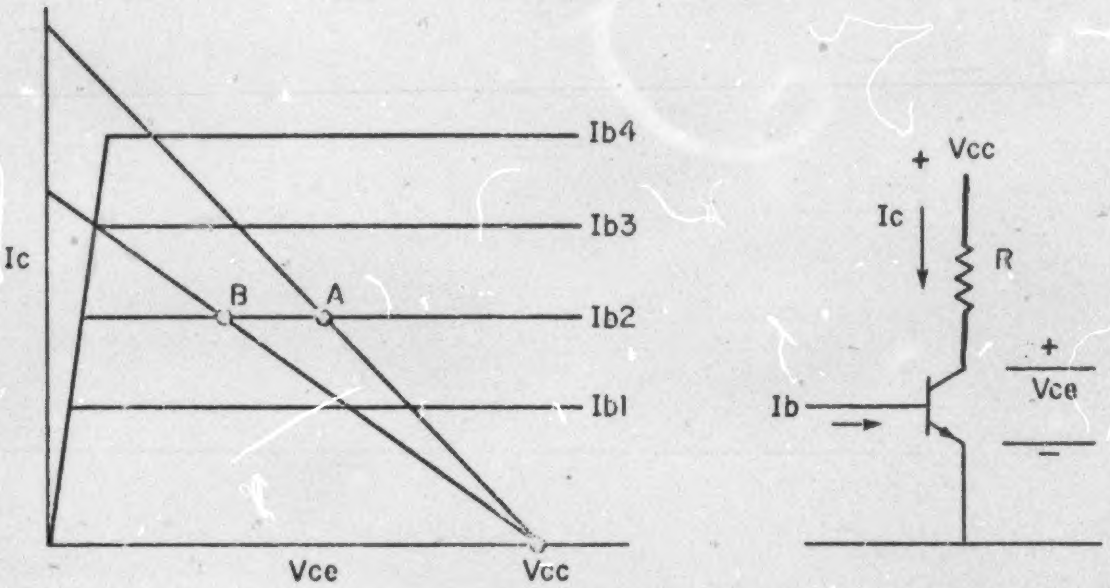


FIG. 14

Fig. 14 shows a family of collector characteristic curves for an *ideal* transistor, as well as the load lines for two different collector resistors. These curves are plots of collector current vs. collector voltage for various values of base current. You'll notice that beyond a certain minimum value of collector voltage the collector current remains constant with variations of collector voltage for a given value of base current. Now, in Fig. 14, you can see the effect of changing the resistance of the collector load resistor. As the resistance increases, the operating point of the transistor shifts from A to B. The current through the resistor thus remains the same while the voltage across it *rises*.* Earlier we explained that this is exactly what a resistance "experiences" when driven by a current source; so you can now see how a transistor can behave like a current source.

---

*The voltage *across* the resistor is the source voltage V_{cc} minus the collector-emitter voltage V_{ce}.

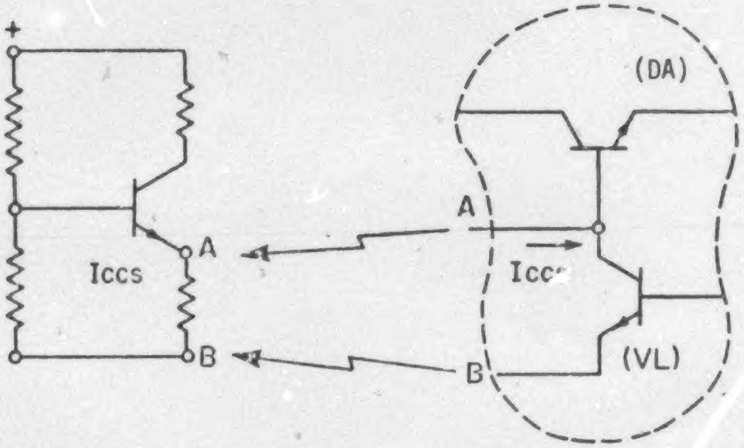


FIG. 15

Thus the amplifier shown in Fig. 15 will make a good current source for the IP-28 if instead of driving a collector load resistor of A-B as shown, it drives the VL and DA of the regulator.

Unfortunately reality is almost never as neat as our idealizations of it, and the circuit in Fig. 15 above still falls short of being a perfect current source. In particular, the collector current does vary somewhat with load resistance because the change in collector-base voltage caused by large variations of load resistance affects the emitter-base circuit. This effect in turn causes changes in emitter current and consequently in the collector current too.

A real transistor therefore generates curves which look more like the ones shown in Fig. 16 below. You'll notice that they are not "flat" like those of the "ideal" transistor but tilt upwards, showing an increase in collector current with collector voltage. A careful look at the operating points A and B on these curves shows that the current through an associated load resistor decreases slightly as the resistance is increased. Because of this, a real transistor approximates an ideal current source, but doesn't, as you see, quite make it.

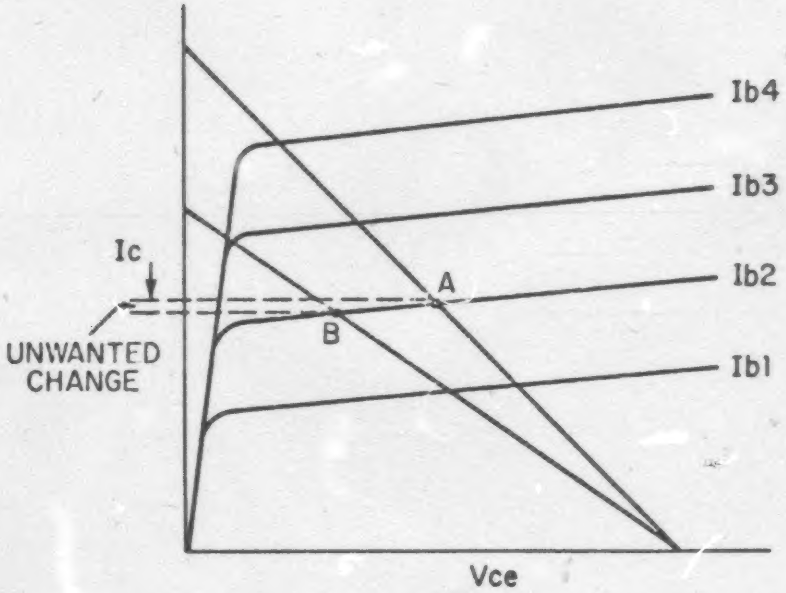


FIG. 16

To eliminate such "second order" effects, the more complex current source of the actual IP-28 incorporates an additional transistor Q1 which replaces Rx of the simpler source. This is depicted in Fig. 17.

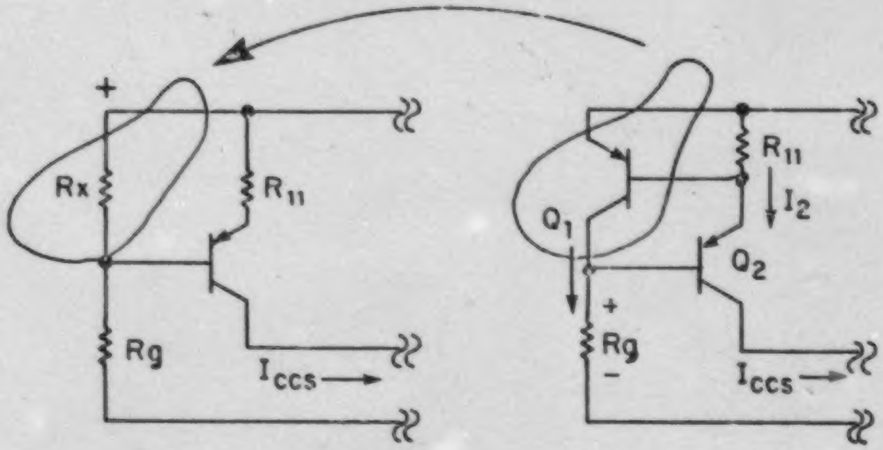


FIG. 17

The additional transistor Q1 behaves as an amplifier. If you study the configuration closely you will see that the input to this amplifier is the voltage drop across R11 caused by the emitter current, I2, of the original current source transistor. This amplifier's collector load resistor is R9, and its collector current develops a proportional voltage across R9. The voltage across R9 biases Q2; if it changes, so will the output current of Q2. Now consider what happens if a large decrease in collector load resistance of Q2 has caused an unwanted increase in Q2's emitter current. As I1 increases, Q1 conducts more heavily and, as a consequence, more current flows through R9. The voltage across R9 thus increases. As a result, the bias on Q2 decreases, and this in turn acts to decrease the emitter current of Q2.

The addition of Q1, then, is a way of adding local negative feedback to correct the deficiences of the single transistor current source. Acting as an amplifier, Q1 amplifies small variations across R11 caused by variations in Q2's emitter current and drives the base of Q2 in a compensatory direction; that is, it drives the base in a direction which cancels the original charge. In this manner, the emitter current of Q2 is stabilized and this makes the collector current of Q2 very constant. You'll probably now recognize Fig 17 as being identical to the current source schematic in Fig. 9.

VOLTAGE LIMITER (VL)

We have already explained the simple action of Q5 as it draws more or less current away from the control input of the regulating element and have already called the module containing Q5 the VL or Voltage Limiter. The VL in the actual IP-28 is identical to the VL of our simplified IP-28.

VOLTAGE REFERENCE SUPPLY (Vref)

The voltage reference supply in Fig. 9 is an augmented version of the one in Fig. 5. T2, D3, C1, R3 and D4 form a half-wave rectifier, filter and zener diode regulator which you'll recognize to be identical to the reference supply of the simplified IP-28. The other components D5, R5, R6, and C2 form an additional zener diode regulator which has been cascaded with the first one.

Perhaps you are wondering why it is necessary to place a regulator after a regulator. The reason for this is that the reference voltage source must be very very stable, since the output of the power supply can be no more accurate than its reference voltage. If the reference voltage shifts, so will the output voltage.

Now, the output fluctuation amplitude of a zener diode regulator is at best about 1% of the fluctuation amplitude at its input. If that is so, a second zener regulator cascaded with the first will yield a fluctuation amplitude that is 1% of 1% of the primary input fluctuations. Such a figure (.01%) is necessary for a reasonable reference voltage source and this is the reason for the added complexity of the actual reference supply.

CURRENT LIMITER (CL)

There is an additional function added in the real IP-28 which has not been covered by our previous discussion and which has not been included in the simplified version. That function is a protective one. Since it is possible (by short-circuit or suddenly lowered load resistance) to draw excessive currents from the supply that would be damaging to either the supply itself or to the circuits which it powers, some means must be included to limit the current to a safe value.

Q6, R13, R14, and R15 form the additional module which does the current limiting. Notice that the load current passes through R13, R14, and R15 which have relatively low resistance and that the voltage drop across these three resistors is placed directly across the base-emitter junction of Q6. Clearly, this voltage drop will rise as the load current rises. As long as this drop does not reach the value of base-emitter voltage required to "turn on" Q6, the latter remains effectively out of the circuit. However, when the output current of the power supply reaches a certain value, the voltage drop becomes high enough to drive Q6 into an active state and collector current begins to flow from the current source into the load.

Since the current source delivers a constant current, there is less available to drive the regulating element and the power supply shuts down, i.e. refuses to deliver any more current. We should mention that when this happens, the power supply undergoes a transition to a different mode of operation. The main feedback element is now the chain of resistors across the base-emitter of Q6, and it senses output current instead of output voltage. In effect, the power supply has shifted mode and instead of operating as a voltage source, it now operates as a current source (though not a very accurate one). It is well worth your time to study this transition using the experimental facilities of SOPHIE.

OUTPUT FILTER (OPF)

The last module is the easiest to describe since it has only two components, a very small series resistor (R16), and a large capacitor (C5) across the output of the supply. This module is the output filter (OPF) and as such it has, strictly speaking, an "AC" function. We won't talk very much about this AC function, because we are primarily interested in the DC behavior of the supply. However, please keep in mind that faults of the OPF have serious consequences for the DC operation of the supply and this is why it has been included in the functional diagram.

We have now covered all seven of the functional modules (DCS, CCS, DA, VL, CL, OPF and VREF) into which the IP-28 has been decomposed. Such a decomposition greatly facilitates troubleshooting of the supply. You will soon have lots of practice in thinking in terms of these functional modules when trying to find a fault in the instrument.

CONTROLS

You have probably noticed that we have not yet discussed or introduced a way of adjusting the output voltage, or changing the current at which the supply limits, or of changing ranges of operations. This is best done now, at a point where, hopefully, you have a good grasp of the role of each module in the operation of the supply as a whole.

The Voltage Control (VC) and Voltage Range Switch

You have already seen that the regulator functions by adjusting the value of output voltage to equal (within a small constant due to the input junction drops of the VL) the voltage of the reference supply VREF. Clearly if VREF changed, so would the output voltage of the supply. Thus, varying the output of VREF is one way of varying the output voltage. It is easy to do this by connecting a potentiometer across the output of the reference supply and "picking" of values of reference voltage from its sliding arm. You can see this in Fig. 8. Note that the VC is shown as set to a position resulting in maximum output voltage. Gross changes in output are made by a switch (VR) which changes the value of a dropping resistance in the reference supply by shorting out one of that resistance's component resistors. This switch is not shown in Fig. 8, but can be seen in the schematic in the vicinity of R5 and R6.

Current Control (CC) and Current Range Switch (CR)

The value of output current at which the CL begins to limit is determined by a string of three resistors through which the output current flows. These three resistors R13, R14, and R15 are connected across the base-emitter junction of the CL transistor Q6. As you already know when the voltage drop across these resistors reaches the turn-on voltage of this base-emitter junction, the CL begins to conduct and "robs" the DA of its input current thus limiting the output current of the supply. If these resistances are large, the turn on voltage is reached at low currents, while if they are low, the turn on voltage cannot be reached until greater amounts of current flow. A simple way to adjust the current limit is then to make these resistances variable; and as you can see from the schematic, the CC is just a variable resistance, while the CR is a switch which shorts out one of the resistors in its "high" range.

APPENDIX C Pre- and Post-Tests for One-Day Experiment

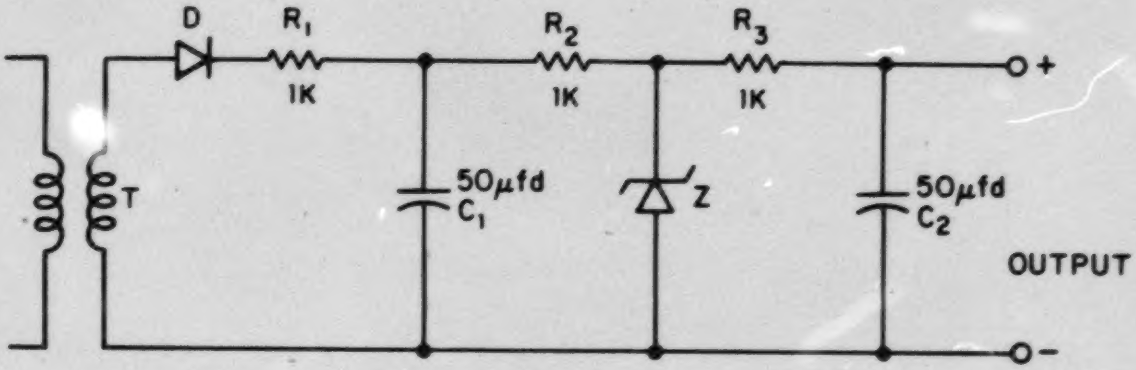
QUIZ V

Name: ______________________________

Please look over this quiz before starting. You have 30 minutes to do 5 problems. If you do not know an answer, just indicate that you don't know and go on. Please do not guess. After trying each problem, you may wish to go back and reconsider those problems which caused you difficulty.

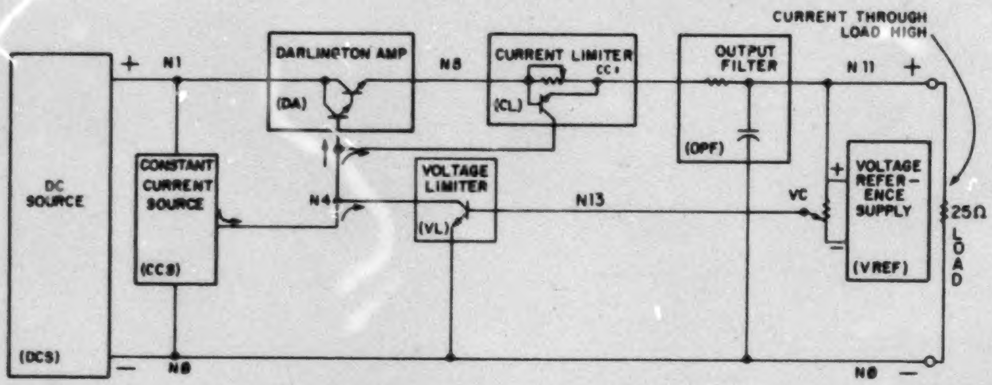
- VI -

In the following circuit, Diode D has been found to be bad. But when it is replaced, it blows again. Please rate the likelihood that each of the listed components is also faulted, bearing in mind this symptom.


D
R₁
1K
R₂
1K
R₃
1K
+
T
50μfd
C₁
Z
50μfd
C₂
OUTPUT
-

Component	Could be at fault	Possible fault, but unlikely	Could not be at fault	Don't know
T	( )	( )	( )	( )
R1	( )	( )	( )	( )
R2	( )	( )	( )	( )
R3	( )	( )	( )	( )
D	( )	( )	( )	( )
C1	( )	( )	( )	( )
C2	( )	( )	( )	( )

Consider the following IP-28 Power Supply which has the indicated symptoms. Which functional blocks could not be faulted? Which ones could be faulted? What fault in each block might account for the observed symptoms?

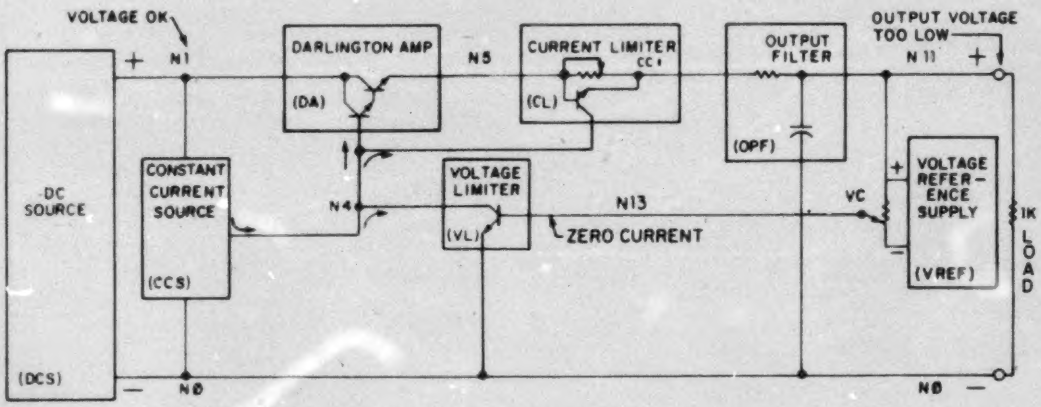

CURRENT THROUGH LOAD HIGH
DC SOURCE
(DCS)
+
N1
−
N0
CONSTANT CURRENT SOURCE
(CCS)
DARLINGTON AMP
(DA)
N4
N5
CURRENT LIMITER
CC+
(CL)
VOLTAGE LIMITER
(VL)
N13
OUTPUT FILTER
(OPF)
N11
+
VC
VOLTAGE REFER-ENCE SUPPLY
(VREF)
25Ω
LOAD
N0
−

SETTINGS
VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=25Ω

Block	Not Faulted	Could be Faulted	Possible Fault
DCS	( )	( )	
CCS	( )	( )	
DARL	( )	( )	
VL	( )	( )	
CL	( )	( )	
OPF	( )	( )	
Vref	( )	( )	

- V3 -

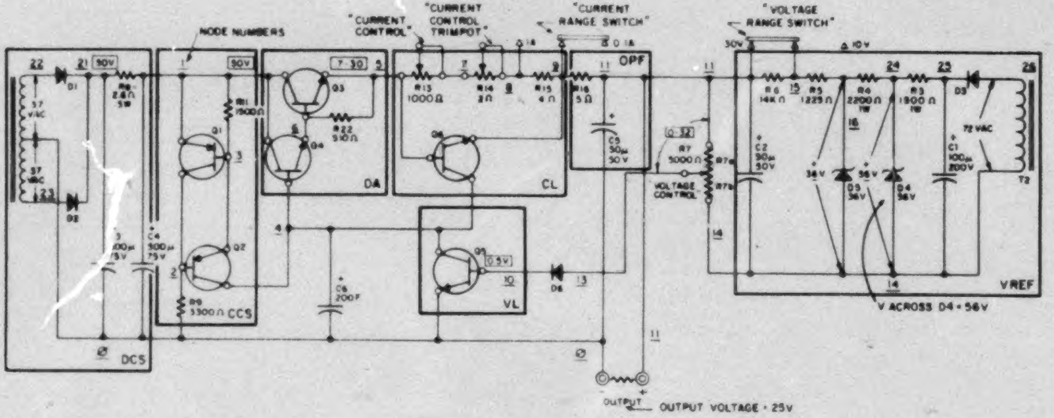
Consider the following IP-28 Power Supply which has the indicated symptoms. Which functional blocks could not be faulted? Which ones could be faulted? What fault in each block might account for the observed symptoms?


VOLTAGE OK
+
N1
DARLINGTON AMP
(DA)
N5
CURRENT LIMITER
CC1
(CL)
OUTPUT FILTER
(OPF)
OUTPUT VOLTAGE TOO LOW
N11
+
DC SOURCE
(DCS)
CONSTANT CURRENT SOURCE
(CCS)
N4
VOLTAGE LIMITER
(VL)
N13
ZERO CURRENT
VC
+
−
VOLTAGE REFERENCE SUPPLY
(VREF)
1K
LOAD
−
N0
N0
−

SETTINGS
VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=1K

Block	Not Faulted	Could be Faulted	Possible Fault
DCS	( )	( )	
CCS	( )	( )	
DARL	( )	( )	
VL	( )	( )	
CL	( )	( )	
OPF	( )	( )	
Vref	( )	( )	

Given the measurements shown for the IP-28 circuit below, make as many reasonable hypotheses as you can about what component might be faulted. Make sure each hypothesis accounts for each of the symptoms in the instrument. For each hypothesis, please say what would be wrong with the part (shorted, emitter open, value too large, etc.).

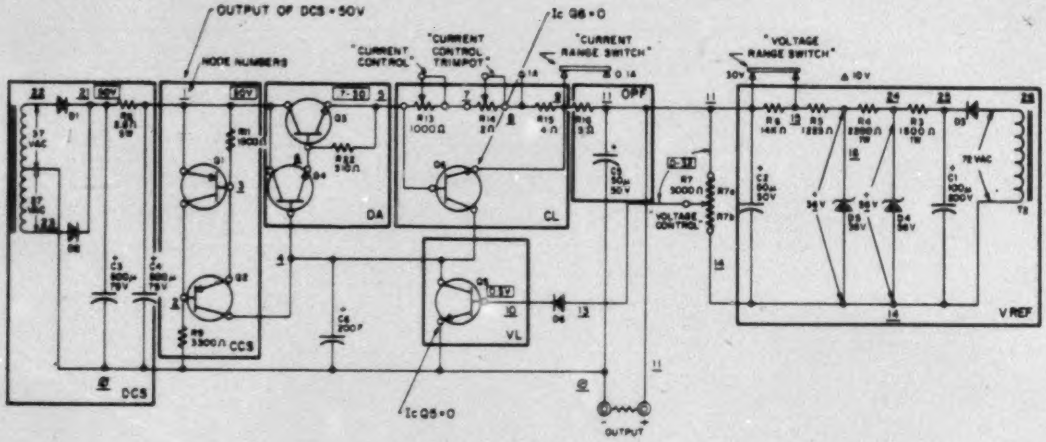

NODE NUMBERS
"CURRENT CONTROL"
"CURRENT CONTROL TRIMPOT"
"CURRENT RANGE SWITCH"
"VOLTAGE RANGE SWITCH"
22
21
90V
D1
D2
37 VAC
37 VAC
23
R8 2.8Ω 5W
C3 100μ 75V
C4 500μ 75V
DCS
1
90V
R1 1500Ω
Q1
3
Q2
2
R9 3300Ω
CCS
7.30
5
Q3
R22 510Ω
6
Q4
DA
4
C6 200F
R13 1000Ω
7
R14 2Ω
8
R15 4Ω
9
Q6
CL
Q5
0.5V
10
VL
D6
13
0.1A
OPF
11
R16 5Ω
C5 50μ 50V
0.32
R7 5000Ω
R7a
R7b
"VOLTAGE CONTROL"
14
30V
10V
R6 14KΩ
15
R5 1225Ω
R4 2200Ω 1W
16
24
R3 1900Ω 1W
25
D3
26
C2 50μ 50V
36V
36V
D5 36V
D4 56V
C1 100μ 200V
72 VAC
T2
VREF
V ACROSS D4 = 56V
Ø
OUTPUT
OUTPUT VOLTAGE = 25V

SETTINGS
VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=1K

	Possible component Fault	Fault mode (CB short, leaky, etc.)
H1:		
H2:		
H3:		
H4:		
H5:		

- V5 -

Given the measurements shown for the IP-28 circuit below, make as many reasonable hypotheses as you can about what component might be faulted. Make sure each hypothesis accounts for each of the symptoms in the instrument. For each hypothesis, please say what would be wrong with the part (shorted, emitter open, value too large, etc.).


OUTPUT OF DCS = 50V
NODE NUMBERS
"CURRENT CONTROL"
"CURRENT CONTROL TRIMPOT"
Ic Q6 = 0
"CURRENT RANGE SWITCH"
0.1A
1A
"VOLTAGE RANGE SWITCH"
30V
10V
22
21
50V
D1
R2 8.2Ω 5W
37 VAC
37 VAC
23
D2
C3 500μ 75V
C4 500μ 75V
DCS
1
50V
R1 1500Ω
Q1
3
Q2
2
R9 3300Ω
CCS
7-10
Q3
Q4
R22 510Ω
DA
4
C6 200P
R13 1000Ω
7
R14 2Ω
8
R15 4Ω
9
R16 3Ω
Q6
CL
Q5
0.3V
10
VL
D6
13
Ic Q5 = 0
11
OFF
C5 50μ 50V
12
OUTPUT
0-32
R7 5000Ω
R7a
R7b
"VOLTAGE CONTROL"
15
R6 145Ω
19
R5 1289Ω
R4 2200Ω 1W
R3 1500Ω 1W
16
24
25
26
C2 50μ 50V
36V
36V
D3 36V
D4 36V
C1 100μ 200V
D5
72 VAC
T2
14
V REF

SETTINGS

VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=1K

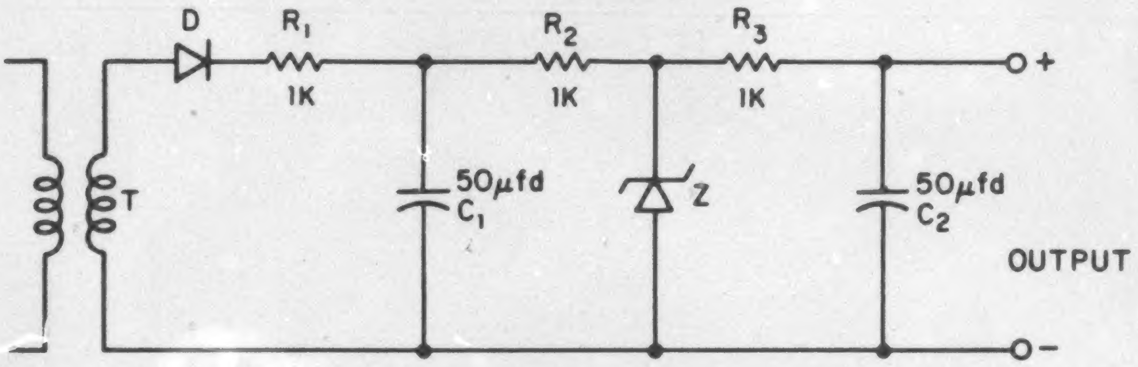
	Possible component Fault	Fault mode (CB short, leaky, etc.)
H1:		
H2:		
H3:		
H4:		
H5:		

QUIZ W

Name: ______________________________

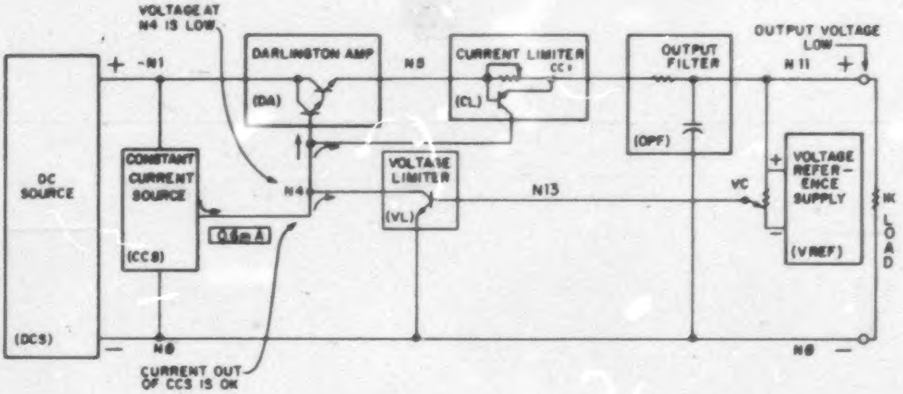
Please look over this quiz before starting. You have 30 minutes to do 5 problems. If you do not know an answer, just indicate that you don't know and go on. Please do not guess. After trying each problem, you may wish to go back and reconsider those problems which caused you difficulty.

In the following circuit, Zener diode Z has been found to be bad. But when it is replaced, it blows again. Please rate the likelihood that each of the listed components is also faulted, bearing in mind this symptom.


D
R1
1K
R2
1K
R3
1K
T
50μfd
C1
Z
50μfd
C2
+
OUTPUT
-

Component	Could be at fault	Possible fault, but unlikely	Could not be at fault	Don't know
T	( )	( )	( )	( )
R1	( )	( )	( )	( )
R2	( )	( )	( )	( )
R3	( )	( )	( )	( )
D	( )	( )	( )	( )
C1	( )	( )	( )	( )
C2	( )	( )	( )	( )

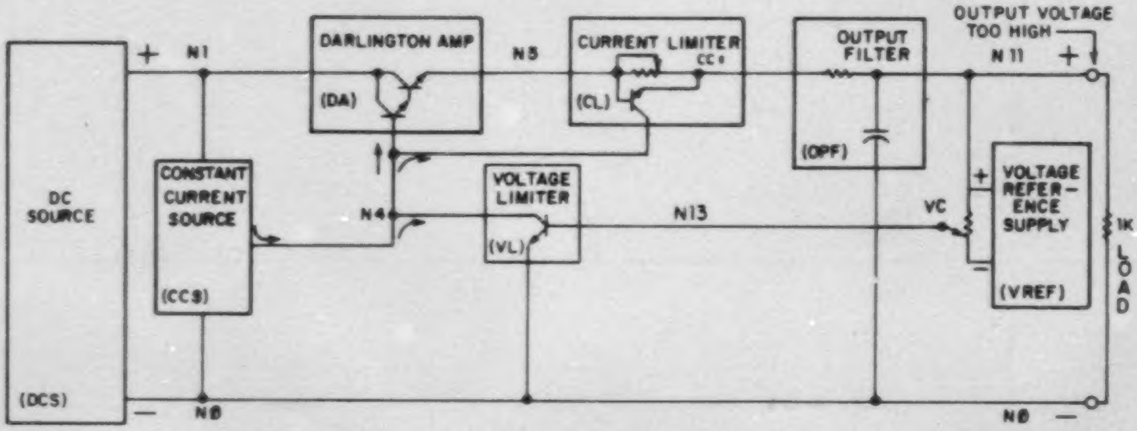
Consider the following IP-28 Power Supply which has the indicated symptoms. Which functional blocks could not be faulted? Which ones could be faulted? What fault in each block might account for the observed symptoms?


VOLTAGE AT
N4 IS LOW
DARLINGTON AMP
(DA)
N5
CURRENT LIMITER
CC
(CL)
OUTPUT FILTER
(OPF)
OUTPUT VOLTAGE LOW
N11
+
-N1
DC SOURCE
(DCS)
CONSTANT CURRENT SOURCE
(CCS)
0.6mA
N4
VOLTAGE LIMITER
(VL)
N13
VC
VOLTAGE REFERENCE SUPPLY
(VREF)
1K
LOAD
N8
−
CURRENT OUT OF CCS IS OK

SETTINGS
VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=1K

Block	Not Faulted	Could be Faulted	Possible Fault
DCS	( )	( )	____________________
CCS	( )	( )	____________________
DARL	( )	( )	____________________
VL	( )	( )	____________________
CL	( )	( )	____________________
OPF	( )	( )	____________________
Vref	( )	( )	____________________

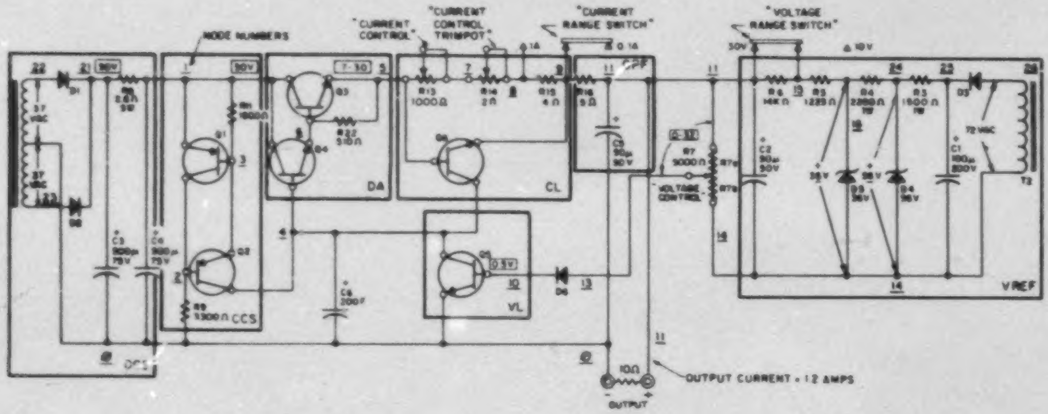
Consider the following IP-28 Power Supply which has the indicated symptoms. Which functional blocks could not be faulted? Which ones could be faulted? What fault in each block might account for the observed symptoms?


OUTPUT VOLTAGE TOO HIGH
DC SOURCE
(DCS)
+
N1
−
N0
DARLINGTON AMP
(DA)
N5
CURRENT LIMITER
CC
(CL)
OUTPUT FILTER
(OPF)
N11
+
CONSTANT CURRENT SOURCE
(CCS)
N4
VOLTAGE LIMITER
(VL)
N13
VC
+
−
VOLTAGE REFERENCE SUPPLY
(VREF)
1K
LOAD
N0
−

SETTINGS
VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=1K

Block	Not Faulted	Could be Faulted	Possible Fault
DCS	( )	( )	____________________
CCS	( )	( )	____________________
DARL	( )	( )	____________________
VL	( )	( )	____________________
CL	( )	( )	____________________
OPF	( )	( )	____________________
Vref	( )	( )	____________________

Given the measurements shown for the IP-28 circuit below, make as many reasonable hypotheses as you can about what component might be faulted. Make sure each hypothesis accounts for each of the symptoms in the instrument. For each hypothesis, please say what would be wrong with the part (shorted, emitter open, value too large, etc.).

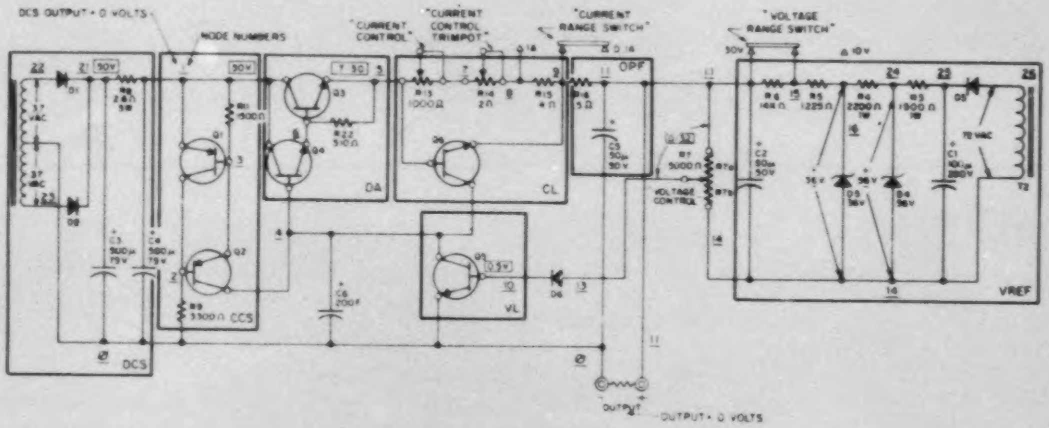

NODE NUMBERS
"CURRENT CONTROL"
"CURRENT CONTROL TRIMPOT"
"CURRENT RANGE SWITCH"
"VOLTAGE RANGE SWITCH"
1A
0.1A
30V
10V
22
21
30V
1
30V
7-30
5
7
8
9
11
D1
R
2.5Ω
5W
R1
1000Ω
Q1
3
Q2
2
R9
1300Ω
CCS
Q3
Q4
6
R22
510Ω
DA
R13
1000Ω
R14
2Ω
R15
4Ω
R16
5Ω
Q5
CL
CPF
C5
90µ
50V
C3
900µ
75V
C4
900µ
75V
D2
4
C6
200F
Q6
0.5V
10
VL
D6
13
12
11
0-31
R7
5000Ω
R7a
R7b
"VOLTAGE CONTROL"
16
R6
14KΩ
19
R5
1225Ω
R4
2200Ω
1W
R3
1500Ω
1W
24
23
26
D3
72 VAC
T2
C2
90µ
50V
18
C1
100µ
200V
D3
36V
D4
36V
14
VREF
37 VAC
37 VAC
10Ω
OUTPUT
OUTPUT CURRENT = 1.2 AMPS

SETTINGS
VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=10Ω

	Possible component Fault	Fault mode (CB short, leaky, etc.)
H1:		
H2:		
H3:		
H4:		
H5:		

- W5 -

Given the measurements shown for the IP-28 circuit below, make as many reasonable hypotheses as you can about what component might be faulted. Make sure each hypothesis accounts for each of the symptoms in the instrument. For each hypothesis, please say what would be wrong with the part (shorted, emitter open, value too large, etc.).


DCS OUTPUT • 0 VOLTS
NODE NUMBERS
"CURRENT CONTROL"
"CURRENT CONTROL TRIMPOT"
"CURRENT RANGE SWITCH"
"VOLTAGE RANGE SWITCH"
22
21
50V
D1
D2
37 VAC
37 VAC
R8 2.6Ω 5W
C3 5100μ 75V
C4 5100μ 75V
Ø
DCS
1
50V
R1 1500Ω
Q1
3
Q2
2
R9 3300Ω
CCS
T 50
5
Q3
Q4
6
R22 510Ω
DA
R13 1000Ω
7
R14 2Ω
8
R15 4Ω
9
0.1A
Q6
CL
1A
R16 .5Ω
11
OPF
C5 50μ 50V
4
C6 200F
Q5
0.5V
10
VL
D6
13
Ø
11
OUTPUT
OUTPUT • 0 VOLTS
0.5V
R7 5000Ω
R7a
R7b
VOLTAGE CONTROL
11
14
30V
10V
R6 148Ω
15
R5 1225Ω
R4 2200Ω 1W
R3 1800Ω 1W
24
23
25
16
C2 50μ 50V
36V
D3 36V
36V
D4 36V
C1 100μ 200V
D5
72 VAC
T2
14
VREF

SETTINGS
VR=HIGH CR=HIGH
VC=1.0 CC=1.0
LOAD=1K

Possible component Fault	Fault mode (CB short, leaky, etc.)
H1: ______________	______________
H2: ______________	______________
H3: ______________	______________
H4: ______________	______________
H5: ______________	______________

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